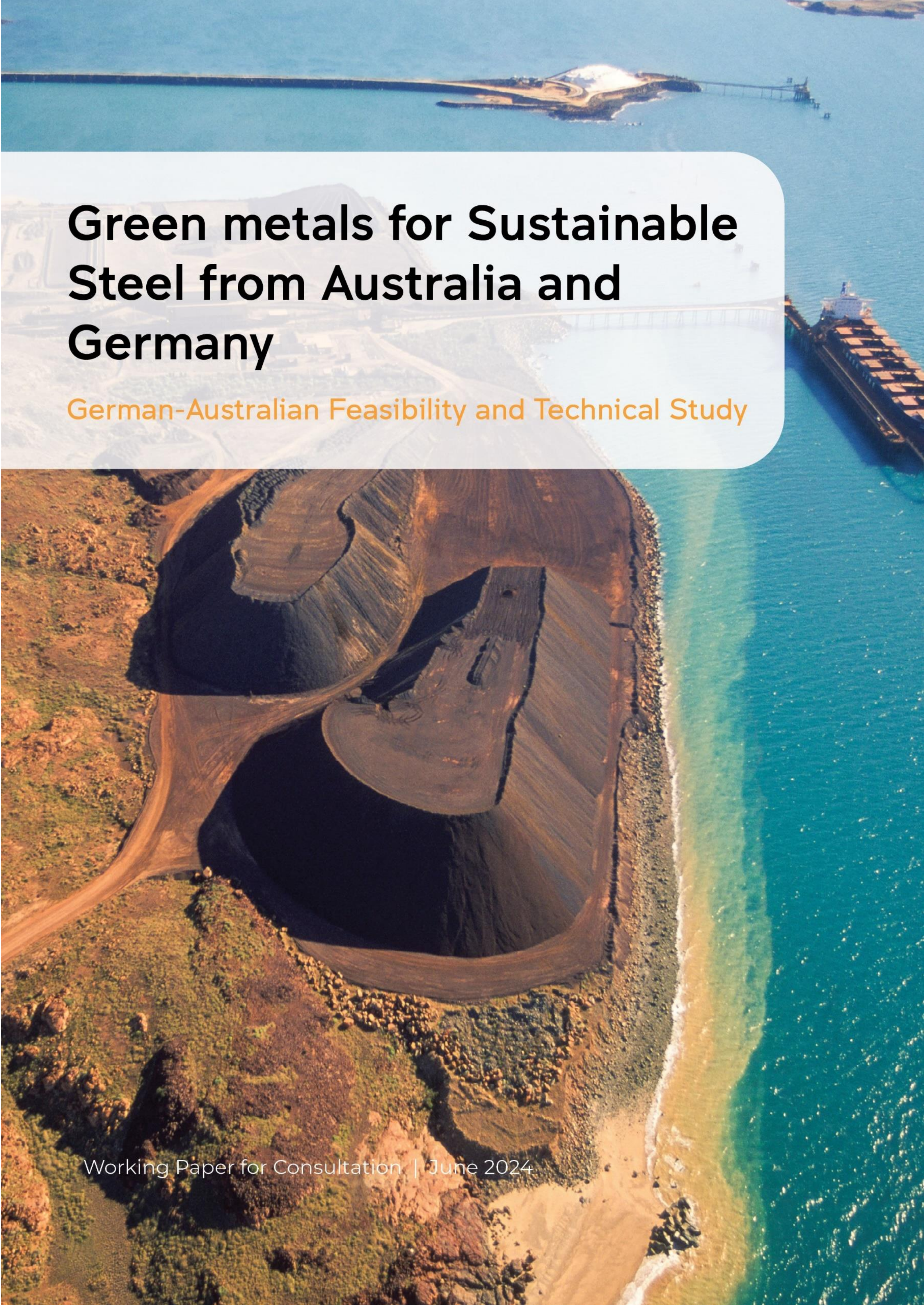
Green metals for Sustainable Steel from Australia and Germany

German-Australian Feasibility and Technical Study



Working Paper for Consultation | June 2024

We welcome and seek stakeholder feedback on this report.
Please contact Dr. Rahman Daiyan (r.daiyan@unsw.edu.au)

Citation

R. Daiyan, I. MacGill, P. Ellersdorfer, C. Wang, I. Canbulat, S. Saydam, T.C. Leung, M.H.A. Khan (2024). 'Green Metals for Sustainable Steel from Australia and Germany: German-Australian Feasibility and Technical Study.' UNSW Sydney, Australia.

Project scope

This report presents the possible case for a green iron and steel supply chain between Australia and Germany. Both countries have significant clean energy and emission reduction targets, and key roles in the global steel industry. At present, Australia is a major global provider of iron ore and coking coal as well as having some local steel production. Germany is renowned for its highly specialised steel industry. This report, focussing on green metal for sustainable steel from Australia and Germany, forms the first part of a series of reports for this feasibility and technical study.

Acknowledgements

The authors thank the Australian industry and research stakeholders who generously shared their time and expertise during the preparation of this report. We also acknowledge the support of the Department of Climate Change, Energy, the Environment and Water (DCCEEW). While the insights and support provided were invaluable, the authors take full responsibility for the content and conclusions presented in the final report.

Disclaimer

UNSW Sydney and the Australian Government do not take responsibility arising in any way from reliance placed in this report. This exercise has been developed based on the finding from a market overview, desktop research and stakeholder consultation and does not necessarily represent the view of Australian Government. This report is not intended to and should not be used or relied upon by anyone else and we accept no duty of care to any other person or entity.

This report contains data and information collected from a wide range of third parties including research, industry and government stakeholders. It draws some tentative conclusions based on this information. The authors have made reasonable efforts to ensure the quality of this analysis but cannot guarantee that the information, assumptions and scenarios that it presents are accurate, complete or appropriate for your circumstances. In particular, this report does not necessarily represent the view of the Australian Government.

Anyone proposing to use information in this report should independently verify and check its accuracy, completeness and suitability for their proposed usage. The report does not constitute technical, economic or commercial advice and to the maximum extent permitted by law, the authors make no representation as to the accuracy, reliability or completeness of the information it provides, have no duty of care and are not liable for any statements or representations in the report.

Executive Summary

The global steel industry is among the most greenhouse gas-intensive sectors globally, accounting for approximately 7-9% of worldwide carbon emissions, and around a quarter of global industrial emissions. However, it also has a key role to play in global decarbonisation efforts given its key role in sustainable built environment, infrastructure and clean energy technologies.

Currently, Europe ranks as the second-largest steel-producing region globally, contributing 267 million tonnes of steel in 2022. Steel contributes an estimated 4% of the European Union's total carbon dioxide emissions. Germany leads as the largest steel producer among European countries, with a 27% share of total production, supported by a workforce of 80,200 employees and a production capacity of 50.6 million tonnes in 2022. Given the carbon intensity and economic significance of the steel industry to the regional economy, both Europe and particularly Germany are actively exploring decarbonisation options for this sector.

Australia currently stands as the largest global exporter of iron ore and metallurgical coal for steel making. Its iron ore industry generates an estimated A$124 billion in annual revenue and directly employs almost 38,000 people. The downstream emissions associated with these iron ore exports are around three times Australia's total national greenhouse gas emissions; this, coupled with Australia's ambitions to become a global net exporter of renewable energy, presents an extraordinary opportunity to have a major emissions impact globally, as well as adding value to Australia's exports. This report highlights the potential opportunities and synergies between Australia and Germany in establishing a green metal supply chain that can be used for ironmaking and steelmaking in Germany. Such collaboration not only facilitates the decarbonisation of the German iron and steel industries but also opens new export opportunities for Australia.

Australia's Competencies as a Green Exporter

Australia boasts one of the largest pipelines of renewable hydrogen projects in the world. Additionally, Australian iron ore and steel companies are exploring the prospect of green iron and steel export. This coupled with Australia's track record for the development of large-scale energy export projects, reinforces the view that Australia can and will play a pivotal role in the future exports of green energy and related products. Australia's leading position in the existing global steel industry, combined with the country's clean energy and renewable hydrogen plans and demonstrated capabilities in large infrastructure projects, represents one of the most promising pathways for Australia to support global emission reductions. This also presents significant opportunities for local economic value addition, new manufacturing ventures, and export prospects for Australian industry.

These competencies are further emphasised by recent funding announcements including A$4 billion for the Hydrogen Headstart program, A$300 million for the Advancing Hydrogen Fund, over A$500 million for the Australian Regional Hydrogen Hubs Program, up to A$3 billion from the National Reconstruction Fund for renewables and low emissions technologies and the announcement of a A$1.7 billion Future Made in Australia Innovation Fund focussing on priority industries including green metals. Additionally, proposed tax incentives, such as the Hydrogen Production Tax Incentive, will provide a A$2 incentive per kilogram of renewable hydrogen produced for up to ten years per project, as well as the Critical Minerals Production Tax Incentive which offers a tax offset of 10% for the costs of processing critical minerals currently listed in Australia.

Synergy with European Iron and Steel Market

Europe and Germany are exploring options to decarbonise their iron and steel production. Australia currently only exports around 0.6 million tonnes of iron ore to Europe annually. However, the synergy of abundant renewable energy, iron ore resources and strong international relationships has the potential to establish a value-added supply chain between Australia, Germany, and Europe, fostering the production and export of green iron, steel, and related products. Collaborative projects such as *The Australia-Germany Hydrogen from Renewable Energy Supply Chain Feasibility Study (HySupply)* and *German-Australian Hydrogen Innovation and Technology Incubator (HyGate)* have already set a foundation for research and industry collaborations between the two countries that could support the development of a green metals supply chain between Australia and Germany.

Table of Contents

List of Figures

List of Tables

1 The Case for Green Iron and Steel

Iron and steel are critical drivers of the global economy and will play a key role in supporting the transition to net zero; however, the conventional ironmaking and steelmaking processes are heavily reliant on fossil fuels. The need an opportunity to reduce emissions from these industries is an emerging frontier for achieving a net zero future.

1.1 Global Importance of the Iron and Steel Industry

Steel, with a global annual production of **1.9 billion tonnes**, ranks as the third most abundant man-made material worldwide, surpassed only by cement and timber.[1] Its recent historical significance and industry growth traces back to the 1850s, marking the advent of widespread commercial and cost-effective production.[2] Today, the steel industry directly employs an estimated 6 million people, generating a total of **US$2.5 trillion** in revenue globally,[1] and is a cornerstone in construction, machinery, and automotive industries.[3] As one of the most traded commodities globally, steel production operates in a competitive international market. Asia is currently the dominant steel producing region contributing 77.4% of the global production in 2023, this is following by Europe at 7.30% with Germany leading production in that region (**Figure 1**).[4] The global demand for steel is expected to rise by more than one third through to 2050.[1] Indeed, steel has a key role in global clean energy transition given its role in building a more sustainable built environment, infrastructure and clean energy technologies. With immediate growth projected at 1.7% in 2024 and 1.4% in 2025, reaching a total production of 2 billion tonnes by the end of 2025.[5] Specifically, steel consumption in the EU is anticipated to rise by 4% and 2% in 2024 and 2025, with production expected to increase by 4% and 0.7% in the same years.[5]

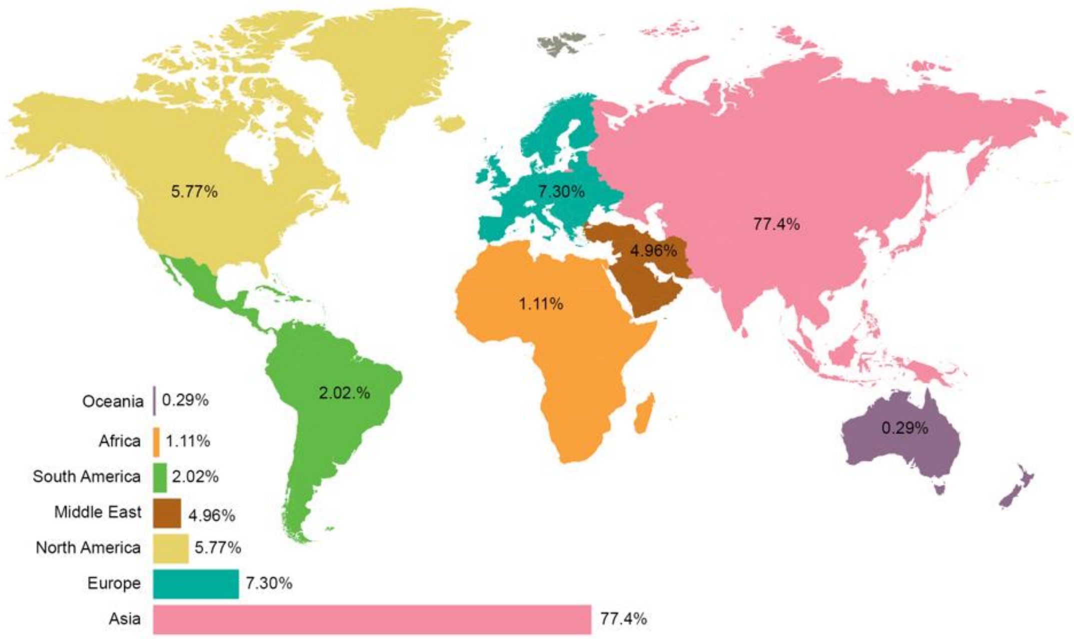


Figure 1. Map of Steel Production by Region. Data based on 2023 crude steel production, taken from World Steel Association.[4] Asia dominates global steel production holding a share of 77.4%, this is followed by Europe with a share of 7.30%.

Critical to steelmaking is the preliminary step of processing iron ore to produce iron, followed by the processing of iron to produce steel. In 2023, global iron ore production reached 2,455.7 million tonnes, leading to the production of 1,300.7 million tonnes of pig iron. Despite iron ore being heavily traded, amassing a trade value of US$159 billion in 2022,[6] the export of iron remains relatively small, with less than 1% of pig iron (12.1 million tonnes) exported in 2023.[4] This is because iron ore processing, ironmaking, and steelmaking are typically conducted in close proximity with integrated steel plants.

1.2 The Current Approach to Ironmaking and Steelmaking

The primary inputs to steelmaking are iron ore, a reductant (mainly metallurgical coal or natural gas), energy, limestone, and steel scrap. *Primary production* refers to steel produced from iron ore, while *secondary production* refers to steel produced from scrap metal. Primary steel production comprises three key phases: raw material preparation, ironmaking and steelmaking (**Figure 2**).[1]

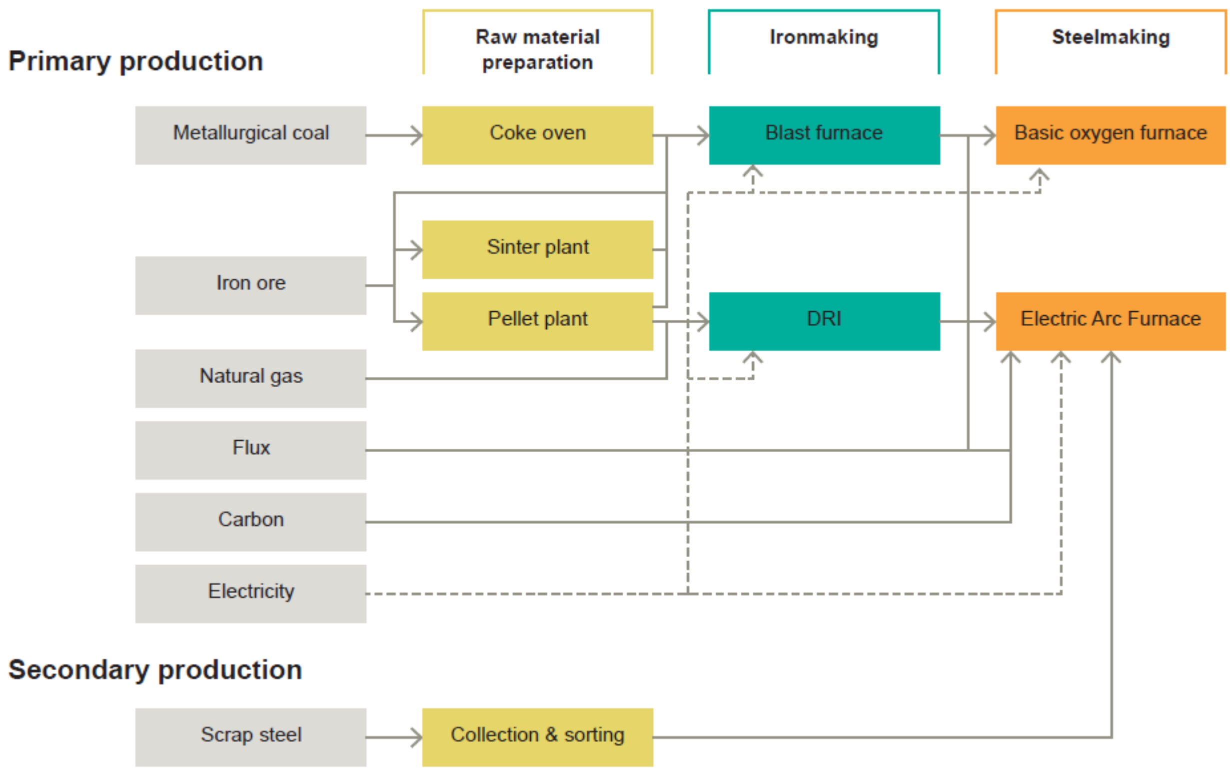


Figure 2. Current Pathways for Iron and Steel Production. The BF-BOF and DRI-EAF processes combined account for 95% of global steel production.[1] This graph is derived by the authors from IEA material under the under the CC BY 4.0 license: IEA 2020 Iron and Steel Technology Roadmap Towards More Sustainable Steelmaking[1] and the authors are solely liable and responsible for this derived work. The derived work is not endorsed by the IEA in any manner.

Currently, the most common primary production pathway is the blast furnace-basic oxygen furnace (BF-BOF) route, which accounts for around **70% of global steel production** and around **90% of primary production**. In this process, coke (derived from metallurgical coal) is used as the reducing agent for iron ore in the blast furnace, producing iron at temperatures up to 1500°C. The resulting iron is then directly fed into the basic oxygen furnace (BOF), where oxygen is injected to lower the carbon content of the iron from 4-5% to the required level for the specific steel grade (typically around 0.25%).[1] The second most common pathway for primary steel production is the direct reduced iron-electric arc furnace (DRI-EAF) route. In this process natural gas is typically used as the reducing agent for iron ore (although coal can also be used).[7,8] The resulting iron is then fed into an electric arc furnace (typically alongside 15-25% scrap metal) to produce steel.[1] Although much of steelmaking is performed as an integrated process, ironmaking and steelmaking can be separated. This allows iron to be produced from iron ore and then transported or shipped to a different facility for steelmaking.

1.3 Carbon and Energy Intensity of the Iron and Steel Industry

The iron and steel sector accounted for 39.6 EJ of energy consumption in 2022, representing **24% of industrial energy use** (see footnote[1]). The primary energy input in the steel sector is coal, making up nearly three quarters of the sector's energy use.[1] Most of the coal that is used is metallurgical coal, used to produce coke for use in blast furnaces, although other grades of coal are also used, mostly to provide industrial heat for the steelmaking process. Global consumption of metallurgical coal reached 1,101 million tonnes in 2023, with the steel sector driving its demand.[12]

Electricity and natural gas account for most of the remaining energy demand in the iron and steel sector, in almost equal measure. The steel industry accounted for **2.5% of global gas demand** and **5.5% of global electricity demand** in 2019.[1] Both energy carriers are used for a wide range of processes in the steel industry, including finishing processes such as rolling, with a considerable proportion of the electricity used to power EAFs, and much of the natural gas used in DRI and natural-gas injection BF-BOF production.[1]

The global steel industry stands as one of the most greenhouse gas intensive industries worldwide.[13] It is responsible for an estimated 7-9% of global carbon emissions, equating to approximately **2.5 to 2.6 billion tonnes of carbon dioxide annually**.[14,15] Notably, steelmaking is currently responsible for **4% of the European Union's total carbon dioxide emissions**.[16] The emissions and energy intensity for each production route are provided in **Table 1**.

[1] Calculated based on an average energy intensity of 20.99GJ/ton[9], a total global steel production of 1885 million tons,[10] and a total energy use of the industrial sector of 166EJ in 2022.[11]

Table 1. Emissions and Energy Intensity of Steelmaking.[9]

	Emissions intensity (tCO_2/t_{Steel})	**Energy intensity** (GJ/t_{Steel})
Global Average[1]	1.91	20.99
BF-BOF	2.33	23.98
DRI-EAF	1.37	22.37
Scrap-EAF	0.68	10.20

1. Global average determined based on the weighted average of each of the production routes (72% BF-BOF, 7% DRI-EAF and 21% Scrap-EAF)[9]

In recent decades, the expansion of steel production has led to a significant increase in both total energy demand and carbon dioxide emissions (**Figure 3**). The ongoing growth in global steel demand,[5] driven by population and GDP growth as well as clean energy infrastructure and technologies, indicates a continued upward trajectory. To align with the objectives of the Paris Climate Agreement, specifically aiming to limit global warming to below 2°C, substantial reductions in energy demand and carbon dioxide emissions are imperative by 2030 and beyond despite growing steel use.[1,13]

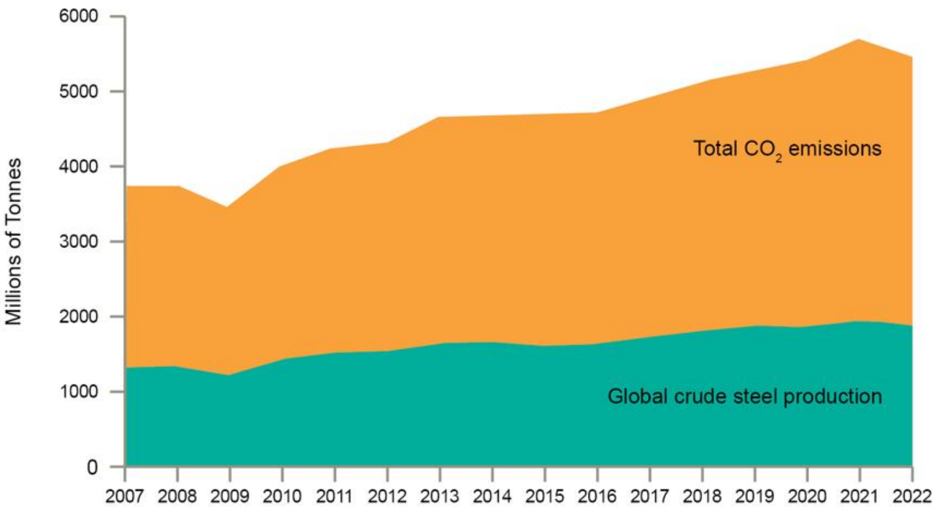


Figure 3. Global Carbon Emissions from Crude Steel Production (2007-2022). During this period, global steel production has seen an average compound annual growth rate of 2.4% and a corresponding average compound annual growth rate of 2.8% in carbon emissions.[9]

1.4 The Definition of Green Iron and Steel

Emerging policy and industrial consensus have highlighted the potential for green iron and green steel. This encompasses environmentally friendly and sustainable iron and steel production methods, entailing the utilisation of renewable energy sources, the reduction of carbon dioxide emissions, and proactive measures to minimise, recycle, and manage waste throughout the manufacturing process.

Despite its growing significance, green iron and steel presently lack a universally accepted industry-wide definition. In recent years, various approaches have emerged, attempting to define and categorise green steel. Notably, standards, protocols, initiatives, and policies in this domain often focus on specific aspects, such as steel producers, the demand side of steel procurement, or financial and funding considerations, either individually or in combination.[13] This diversity in focus reflects the nuanced and multifaceted nature of defining and implementing green iron and steelmaking practices.

The World Trade Organisation (WTO) acknowledges that the widespread and fragmented decarbonisation efforts in the iron and steel industry lead to uncertainty, higher transaction costs, and potential trade friction.[17,18] Standards must be globally relevant, technology-neutral, with clear boundaries and scope, ensuring transparency in monitoring, reporting, and verification.[13] In much the same way that a globally uniform definition for green hydrogen is instrumental in developing global green hydrogen trade,[19] a comparable approach is essential for the iron and steel industry to ensure compliant trade and accountable emission reduction.

Multiple ongoing efforts are underway to establish definitions and standards for low-carbon (green) steel. While there is a move towards greater alignment and consensus on terminologies for green steel, definitions are continually being developed and refined. Definitions of green steel should specify the boundary conditions for emissions analysis, including whether it extends beyond scope 1, 2, and 3 emissions (a description of these is provided in **Table 2**).

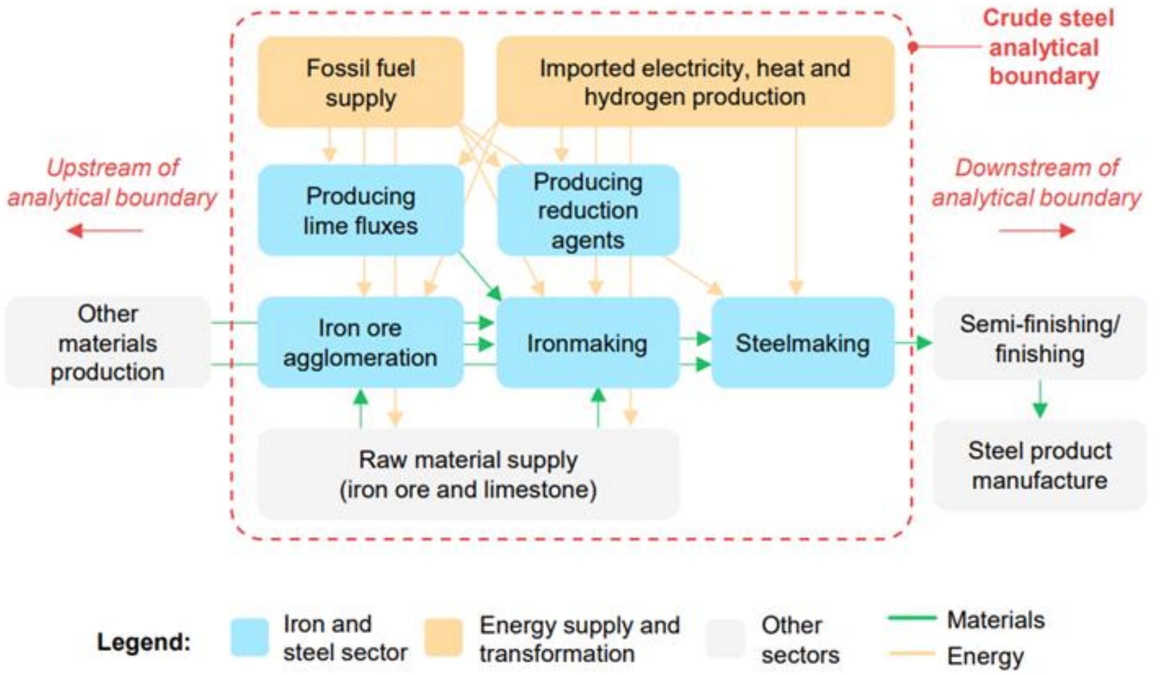
Table 2. Description of Emissions Boundary Definitions

Type of Emissions	Description
Direct	**Scope 1**: Emissions that originate from sources within an organisation's boundaries and result from its activities. These emissions are calculated at the point of release.[20]
Indirect	**Scope 2**: Emissions that stem from activities that produce electricity, heating, cooling, or steam consumed by an organisation but generated outside of its boundaries.[20] **Scope 3**: Emissions that stem from activities occurring outside an organisation's boundary, excluding the production of electricity and other Scope 2 emissions.[20]

The terms that denote the highest decarbonisation ambitions are:[21,22]

- **Near-zero steel**, which refers to the lowest practicable emissions with no removal or offsetting of residual emissions.
- **Net-zero steel**, which refers to the lowest practicable emissions with removal or offsetting of residual emissions.

The International Energy Agency (IEA) offers a product-level definition for near-zero steel emissions intensity, measured in tonnes of CO_2 emissions per tonne of crude steel produced.[21] The specific boundaries for quantifying the IEA's near-zero steel definition emissions are detailed in **Figure 4** and encompass both the ironmaking and steelmaking processes.



Notes: “Other materials production” refers to the production of material inputs to the iron and steel sector besides iron ore and limestone, including electrodes, alloying elements and refractory linings.

Figure 4. Analytical Boundary for IEA Definition of Near Zero Emission Steel Production. Emissions are considered at the product-level and account for scope 1, 2 and 3 emissions for both the ironmaking and steelmaking processes. However, scope 3 emissions are only considered for the production and supply of fossil fuels, limestone, and iron ore. Image reproduced under the CC BY 4.0 license: IEA 2022 Achieving Net Zero Heavy Industry Sectors in G7 Members.[21]

In establishing criteria for near-zero steel emissions, the International Energy Agency (IEA) has implemented an emissions threshold of **0.4 tonnes of CO_2 equivalent per tonne of crude steel** *when the scrap percentage is zero*. In the case of *crude steel production utilising 100% scrap steel*, this threshold is adjusted to **0.05 tonnes of CO_2 equivalent per tonne of crude steel**. Furthermore, the IEA's definition mandates that steel production must incorporate a minimum of 30% scrap steel and adhere to the specified constraints of the sliding scale to qualify as near-zero (green) steel.[13,21] This is detailed in **Figure 5**.

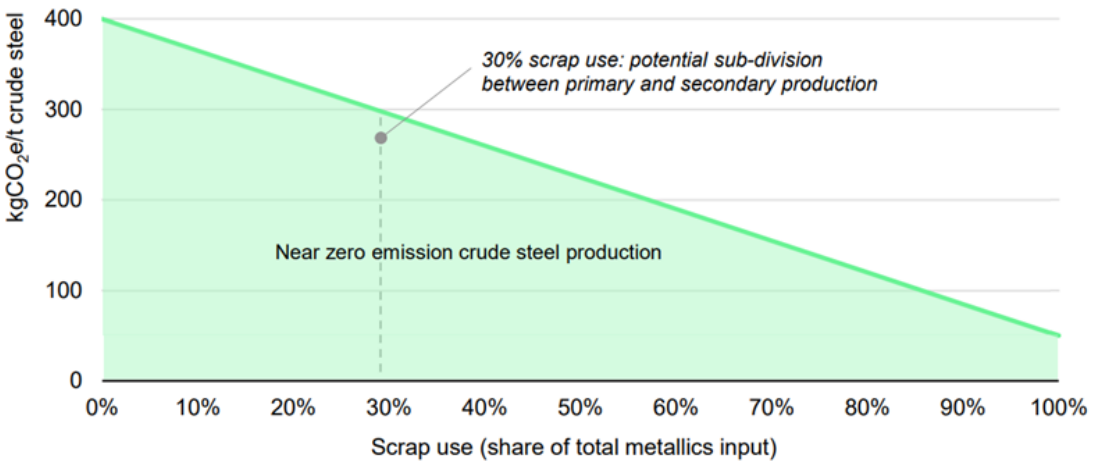


Figure 5. Near Zero Emission Crude Steel Production Threshold as a Function of Scrap Use. The IEA definition of green steel requires scrap-use of 30% or higher and an emissions intensity which sits on a sliding scale, depending on the amount of scrap metal used (ranging from $0.3tCO_2/t_{Steel}$ (for 30% scrap use) to $0.05tCO_2/t_{Steel}$ (for 100% scrap use). Scrap metal refers to used metal which can be reprocessed and recycled into new products. Image reproduced under the CC BY 4.0 license: IEA 2022 Achieving Net Zero Heavy Industry Sectors in G7 Members.[21]

In 2022, the German Steel Federation expanded on the IEA's green steel definition, introducing foundational elements for a green steel definition, encompassing a classification system and a customer-oriented labelling approach for “climate-friendly” steel.[23] In addition to the use of a sliding scale as function of scrap use (as set out by the IEA), the German Steel Federation includes a classification system comprising five categories. These range from D (lowest ambition level) to A (highest ambition level), with level A denoting near-zero emission steel produced exclusively from renewable energy sources.

The classification system aims to guide green steel markets, establishing requirements and crediting modalities for the utilisation of green steel in various applications. It also allows for adjustments over time in alignment with climate policy ambitions. On the other hand, the labelling system is designed to provide steel customers with information regarding the level of decarbonisation in the production process, complemented by the product carbon footprint of the end-product.[23] A summary of current definitions of green steel is provided in **Table 3**.

Table 3. Summary of Various Green Steel Definition Emission Thresholds and System Boundary [13,18,23]

Organisation / Initiative	Quantitative Threshold (tCO_2/t_{Steel})		Emissions Boundary		
	Primary Production[1]	Secondary Production[1]	Scope 1	Scope 2	Scope 3
International Energy Agency (IEA)	0.3[2]	0.05	X	X	partial
German Steel Federation	0.3[2]	0.05	X	X	partial
Science Based Targets Initiative	0.5	0.2	X	X	partial
Climate Bond Initiative	0.12	0.12	X	X	X
ResponsibleSteel International Standard	0.4	0.05	X	X	X
First Movers Coalition (FMC)	<0.4	<0.1			
Mission Possible Partnership	0.5		X	X	partial
Sustainable STEEL Principles	0.2		X	X	partial

1. Primary production refers to the production of steel from iron ore. Secondary production refers to the production of steel from steel scraps.
2. Based on the IEA mandate of utilising 30% scrap metal for green steel production.

2 European and German Iron and Steel Markets

Germany is the largest steel producing nation in Europe, a region which stands as the second-largest steel producing region globally. Moreover, Germany is a major importer of iron ore and is envisaged to be an importer of renewable energy (through energy carriers such as renewable hydrogen and derivatives), creating opportunities for green ironmaking and steelmaking.

European and German iron and steelmakers have been at the forefront of modern iron and steelmaking, dating back to the early stages of the industry's development. The introduction of the Bessemer process in England in 1856[24] and the open-hearth process in Germany and France in 1865[25] marked significant milestones, enabling the cost-effective and large-scale production of steel. The integration of coal and steelmaking played a pivotal role in driving the industrial revolution.[26] Today, European and German steel is internationally renowned for its innovation, quality and environmental performance.[27]

2.1 Importance to EU Economy

2.1.1 European and German Steel

Europe stands as the second-largest steel producing region globally, contributing 267 million tonnes of steel in 2022, of which, **136 million tonnes was produced in the European Union** (EU).[28] With over 500 steel production sites dispersed across 22 EU Member States, the industry has an annual turnover of approximately **€130 billion**, directly and indirectly employing over **306,000 and 1,550,000 personnel within the EU respectively**,[28] and playing a pivotal role as the backbone for development, growth, and employment within the region. The following **Figure 6** outlines the total steel production of each EU steel producing nation in 2022.[28-30]

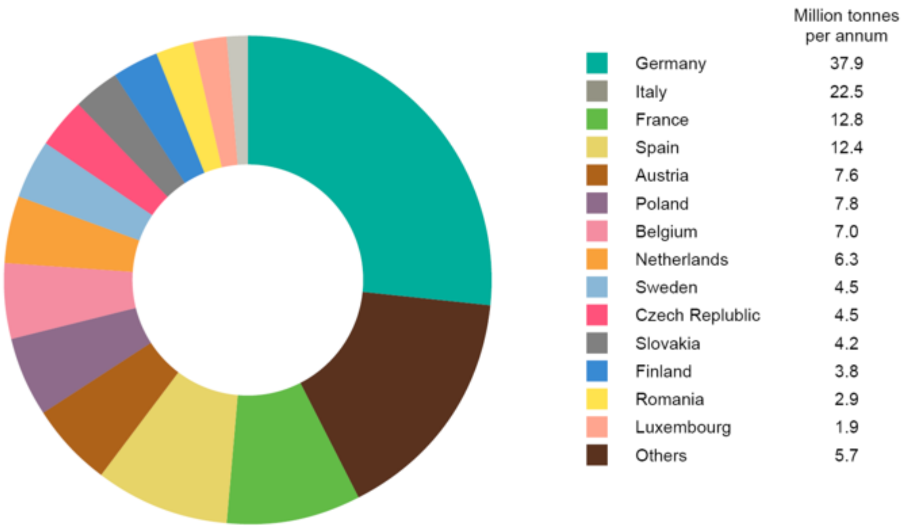


Figure 6. EU steel production by country in 2022.[28-30] Germany leads as the largest steel producer among European countries, with a 27% share of total production.

Germany stands as the largest steel producer among the EU countries (holding 27% of total production), boasting a workforce of 80,200 employees and a total production capacity of **50.6 Million tonnes of steel** in 2022[28]. The following **Figure 7** and **Figure 8** show the total operating and announced iron and steel plants in Germany.

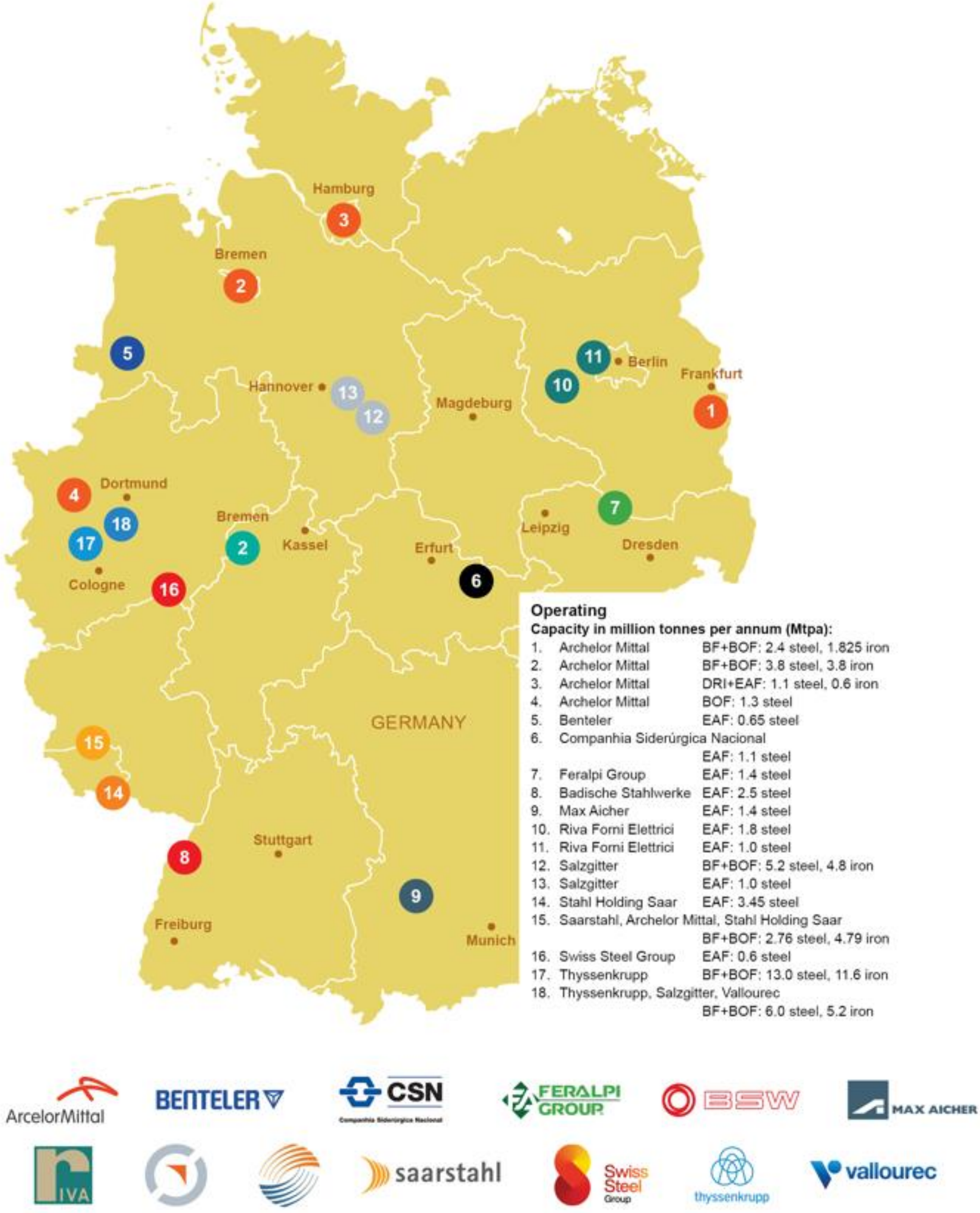
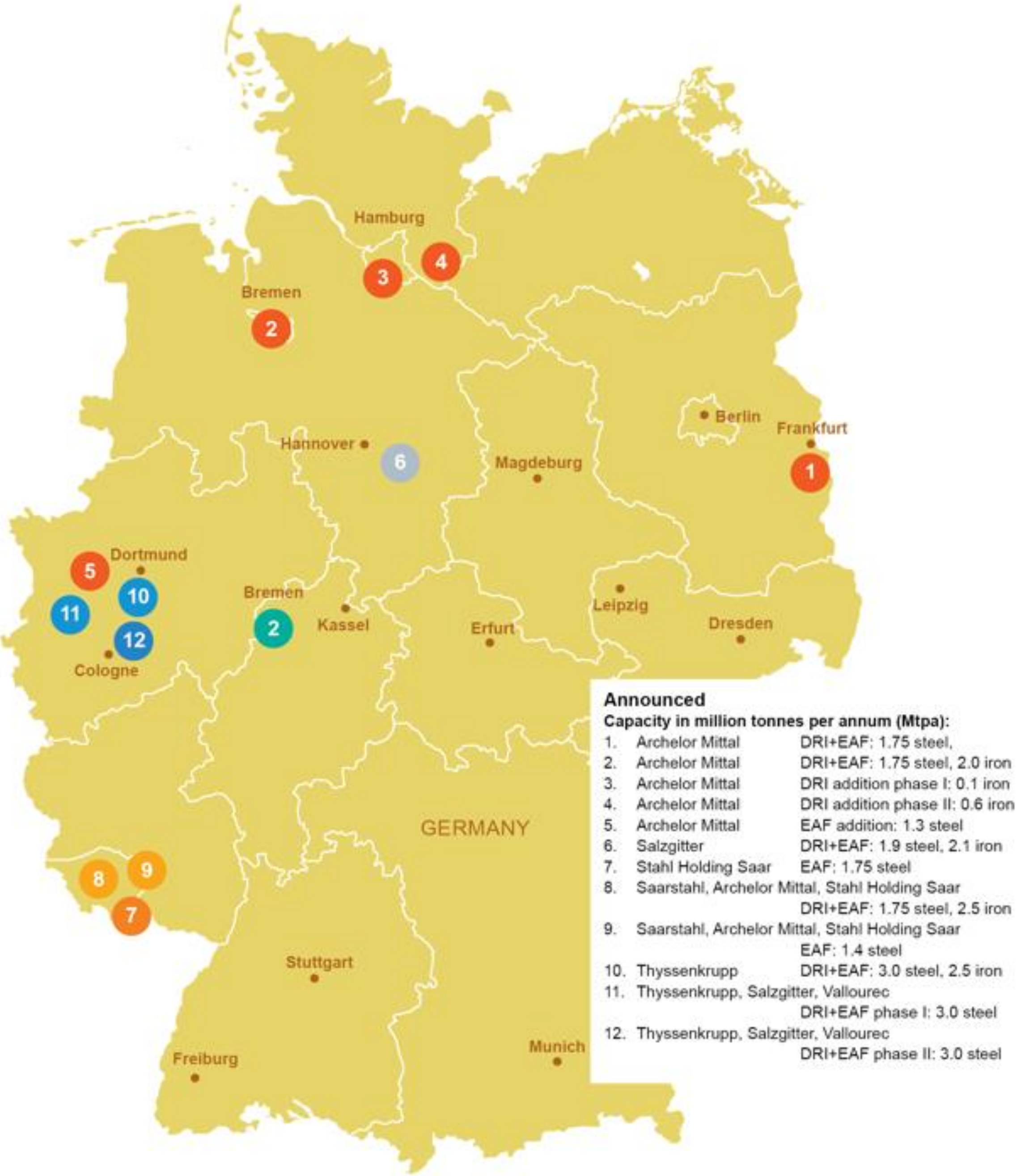


Figure 7. Current Operating Iron and Steel Plant Capacity in Germany. Thyssenkrupp holds the largest steelmaking capacity in Germany, using the most carbon-intensive BF+BOF production route to produce a majority of its steel.



ArcelorMittal saarstahl thyssenkrupp vallourec

Figure 8. Announced Iron and Steel Plant Capacity in Germany. There is still large investment in steel manufacturing in Germany with over 18 million tonnes of announced steel production capacity, driven by ArcelorMittal and Thyssenkrupp.

Major steel products include sheets (hot rolled, cold rolled, coated), flat plates, beams, rebars, wired rods and merchant bars, with a detailed a breakdown for 2022 provided in **Table 4**. Despite substantial production, the EU consumes more steel than it produces. In 2022, steel consumption within the EU surged to approximately **147 million tonnes**, comprising both domestic supply (118.1 million tonnes) and imports (28.9 million tonnes).[28]

Table 4: Total Finished Steel Production in EU[28]

EU Finished Steel Production (Total Hot Rolled)		2022 EU production (million tonnes)
Flat Products	Quarto Plate	10,011
	Hot Rolled Wide Strip	63,641
	Other Flat Products	1,228
Long Products	Wire Rod	18,912
	Rebar	11,518
	Merchant Bars	10,423
	Heavy Sections	7,172
	Other Long Products	2,459

The main consumption of steel are in the construction sector (37%), mechanical engineering (for applications such as machinery, motors and generators) (17%), automotives (15%), metalware (13%) and tubes (12%)[28]. Aggregate numbers for this demand provided in **Table 5**.

Table 5: Steel Demand in EU[28]

EU Crude Steel Output by Quality	2022 EU production (million tonnes)	2022 EU production (%)
Cabon steel	104,981	77.0
Carbon alloy steel	25,244	18.5
Stainless steel	6,096	4.5

Steel comes in a variety of grades, each tailored to specific applications and industries. These grades often possess highly specialised characteristics, such as varying levels of strength, ductility, corrosion resistance, and thermal properties. Europe, and particularly Germany, have established significant expertise in producing these specialised steel grades, which are critical for advanced manufacturing sectors, including automotive, aerospace, and machinery. The ability to produce high-quality, tailored steel products locally not only supports these industries but also reinforces the strategic importance of maintaining robust steelmaking capabilities within the region.

2.1.2 European and German Iron

In 2023, the **EU produced 64.4 million tonnes of iron**, consisting of 64.1million tonnes of pig iron and 0.3 million tonnes of direct reduced iron.[4] In 2022, the EU imported 2.4 million tonnes of pig iron primarily from Russia (1.2 million tonnes), Brazil (0.482 million tonnes), and South Africa (0.322 million tonnes).[31] The EU exported 51,000 tonnes of pig iron, with key recipients including the United Kingdom (11,000 tonnes), Türkiye (11,000 tonnes), and Switzerland (9,600 tonnes).[32]

In 2023, **Germany's pig iron production reached 24 million tonnes**, with an estimated 0.2 million tonnes of sponge iron, as reported by WorldSteel.[4] In 2022, Germany imported 0.42 million tonnes of pig iron, with Brazil (0.14 million tonnes), Ukraine (48 thousand tonnes), and Sweden (34 thousand tonnes) being the major suppliers.[33] Germany exported 0.19 million tonnes of pig iron, with top consumers including Italy (39.7 thousand tonnes), Poland (30.7 thousand tonnes), and France (30.5 thousand tonnes).[33] The majority of Germany's pig iron exports are within the EU, with only around 3 thousand tonnes exported to Asia.[33]

2.2 Reliance on Imports to Fulfill Iron and Steel Production Demand

2.2.1 Iron Ore

Compared to the size of the EU iron and steel markets, the EU lacks sufficient iron ore resources, producing only 30.4 million tonnes (1.3% of the world's production).[34] The major iron ore producing countries within the EU are Sweden (28.5 million tonnes, 2022) and Austria (2.3 million tonnes, 2022), with Sweden dominating supply through four operating mines.[35] The Kiruna Mine in Sweden, the largest mine, holds proven reserves of 365 million tonnes and total resource of 1,437 million tonnes (of grade 38.9-42.4% Fe).[36]

To meet the substantial demand for iron ore in steel production, in 2022 the EU imported approximately 114 million tonnes,[5] with approximately 50% arriving through the port of Rotterdam.[37] Key ports for dry bulk imports crucial for steel production in the EU include the Port of Rotterdam, Amsterdam, Gdansk, Constanta, and Hamburg.[38] Major global iron ore suppliers to the EU include Canada (21.9 million tonnes), Brazil (20.3 million tonnes), Ukraine (12.9 million tonnes), and South Africa (10.5 million tonnes), with Australia contributing only 0.6 million tonnes in 2022 despite being the world's largest exporter.[39]

Notably, **Germany imported 34.4 million tonnes of iron ore** and concentrates (including roast iron pyrites) in 2022.[40] The primary suppliers of iron ore to Germany in 2022 were Canada (10.1 million tonnes), South Africa (9.6 million tonnes) and Brazil (6.7 million tonnes), while Australia only exported about 0.170 million tonnes to Germany in 2022.[40] Germany imports ore through the following ports: Bremen, Brunsbüttel, Emden, Hamburg, Nordenham, Stade, Rensburg, Kiel, Port of Rostock, Sassnitz, Stralsund and Wismar.[41] More than one third of iron ore imports are handled through the German North Sea ports[41] and Hansaport in Hamburg represents Germany's largest seaport terminal for dry bulk cargo, importing more than 40 million tonnes of bulk cargo including iron ore.[42]

2.2.2 Steel Scrap

In 2023, the **EU imported approximately 30.0 million tonnes of steel scrap** and exported a total of 44.7 million tonnes.[4] Although the EU currently has a net export of steel scraps, this is expected to shift to a net import of steel scraps within the next five years.[43] This is driven by the fact that many steel producers within the region are moving towards the use of electric arc furnaces (EAFs) which support steel recycling and produce lower emission steel but typically require an input of steel scraps for operation.[44] Germany imported a total of approximately 3.2 million tonnes of steel scraps in 2023[4] (down from 4.2 million tonnes in 2022[3]) with the Netherlands providing the majority of the steel scrap imports to Germany (at 0.9 million tonnes in 2022) followed by the Czech Republic and Poland (at 0.8 and 0.6 million tonnes in 2022 respectively).[45]

Steel scraps contain elements that cannot be removed easily by current smelting processes, such as chromium, tin, copper, nickel and molybdenum,[46] these are referred to as "tramp" elements and can adversely affect the properties and quality of the final steel product.[47] The EU is experiencing a rise in the import of old scraps (previously used by consumers) compared to new scraps (generated during manufacturing).[46] Currently, old scraps contribute to over 60% of the total steel scrap used in the EU, resulting in an increase in the presence of tramp elements.[46] For EAF production in Germany, the presence of tramp elements could pose significant challenges in the production of high-grade and specialised steels.

The Port of Rotterdam plays a crucial role in the import and export of scrap metal in Europe. Scrap metal from the Netherlands, Germany, and Belgium converges in Rotterdam, where it is sorted and distributed throughout Europe or internationally.[48] Germany imports scrap through the following ports: Hamburg, Leer, Wilhelmshaven, Kiel, Lübeck, Rostocker Fracht- und Fischereihafen and Stralsund.[41]

2.2.3 Metallurgical Coal and Natural Gas

Carbon currently plays a crucial role in steelmaking as a vital additive, predominantly serving as a reducing agent for the reduction of iron oxide to iron whilst also enhancing the carbon content of iron. Commonly, metallurgical coal or natural gas are used as this source of carbon. However, it is worth noting that coal-based pathways result in substantial greenhouse gas emissions and pollution[49,50] compared to natural gas processes. The European Union accounts for approximately 15% of annual metallurgical coal imports in 2022, at (36 million tonnes)[5] with a majority of this coal sourced from Australia and the United States.[51] This is detailed in **Figure 9**.

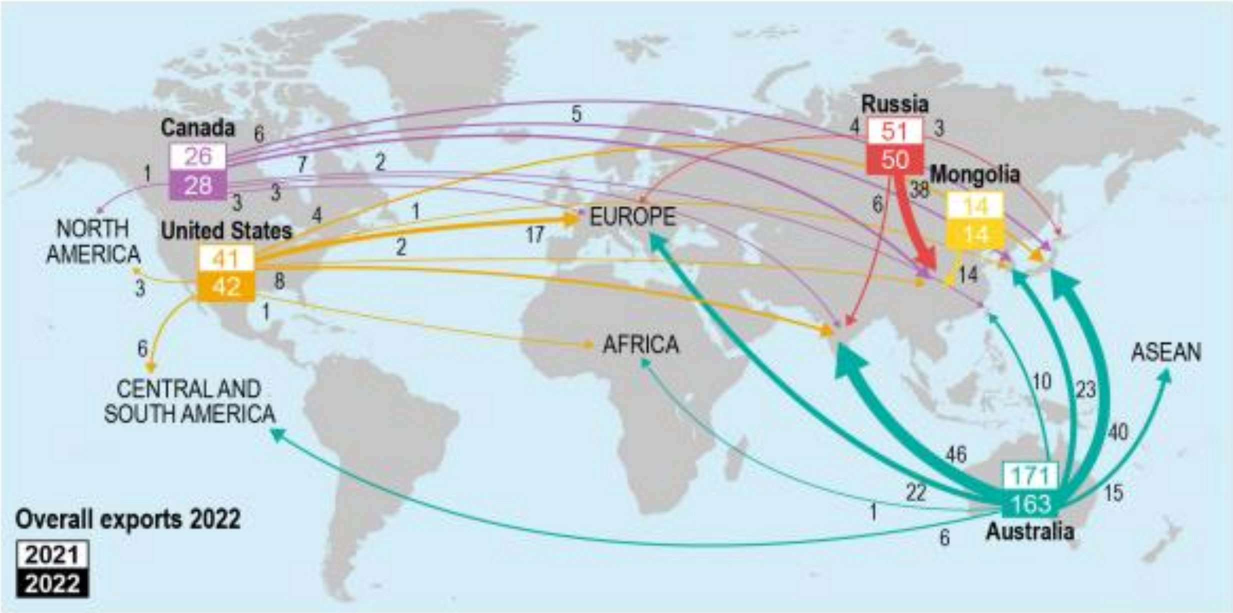


Figure 9. Major Trade Flows of Metallurgical Coal in 2022 (million tonnes). Australia currently represents the largest global exporter of metallurgical coal at a rate of 163 million tonnes in 2022. Image reproduced under the CC BY 4.0 license: IEA 2023 Coal 2023 Analysis and forecast to 2026.[12]

Compared to the rest of Europe, Germany has substantial domestic coal mining operations and is the largest coal producer in the EU, with a production of lignite (brown) coal of approximately 131 million tonnes in 2022.[12] German domestic coal is primarily used for power generation and district heating, with the country relying on imports of metallurgical coal for steel production.[52] In 2022, Germany imported 44.4 million tonnes of coal,[53] maintaining its position as the largest net importers of coal in the EU.[12] Germany imports coal through the following ports: Bremen, Brunsbüttel, Gluckstadt, Hamburg, Nordenham, Stade, Wilhelmshaven, Rendsburg, Flensburg, Kiel, Rostocker Fracht- und Fischereihafen, Port of Rostock, Stralsund and Wismar.[41]

In 2021, the EU imported 83% of its natural gas,[54] with Russia supplying 45% of total gas imports.[55] However, since Russia's invasion of Ukraine, gas imports from Russia to the EU have significantly decreased. This decline has been compensated for by a notable surge in liquefied natural gas (LNG) imports, particularly from the US. Between January and November 2022, Russia (pipeline gas + LNG import) constituted less than a quarter of EU gas imports, with another quarter from Norway and 11.6% from Algeria. LNG imports, excluding Russia (mainly from the US, Qatar, and Nigeria), accounted for 25.7%.[54]

Natural gas accounted for just under a quarter of Germany's primary energy use in 2022, making it the country's second most important energy source after oil.[52] In 2022, Germany imported a total of 1,449 TWh of natural gas. The major contributors to this import were Norway (33%) and Russia (22%), a notable shift from the 52% Russian share in 2021.[56] Germany imports liquefied natural gas through the following ports: Brake, Brunsbüttel, Cuxhaven, Hamburg, Wilhelmshaven and Port of Rostock.[41]

2.2.4 Ferroalloys

A significant portion, specifically 23%, of European steel production is centred on alloy or high-alloy steel.[28] The production of these steel types heavily relies on elements such as chromium, nickel, and molybdenum,[57] collectively termed "ferroalloys." In 2022, the European Union imported 190,806 tonnes of ferroalloys, with Brazil, Colombia, and the Dominican Republic being major suppliers, providing 62,891, 36,592, and 24,774 tonnes, respectively.[58] Germany primarily sources its ferroalloys through regional trade, importing a total of 10,452 tonnes in 2022, with 8,719 tonnes (83%) originating from the Netherlands.[58]

2.2.5 Limestone (Flux)

Flux refers to any material that is introduced into the smelting of iron ore to promote fluidity and to remove impurities from the iron ore in the form of slag[59]. Lime and limestone are the most commonly used materials for flux.[59] International trade in lime products is limited due to the relative abundance of limestone globally coupled with its low value to weight ratio. As a result, lime production is usually localised near markets, minimising the need for long-distance transportation.[60] In 2022, the EU imported the majority of its limestone from Canada, the United Kingdom, and Norway contributing 42%, 20%, and 20% to total imports, respectively.[61] Germany imported a majority of its limestone from within the EU, from France, Poland, Belgium and Austria contributing 25%, 17.8%, 17.5% and 13.1% respectively for a total import of 3 million tonnes in 2022.[62,63] Germany imports lime and limestone through the following ports: Glückstadt, Rostocker Fracht- und Fischereihafen, Port of Rostock, Sassnitz and Wismar.[41]

2.3 Europe and Germany's Transition to Green Iron and Steel

EU policies such as the REPowerEU plan highlights that around 30% of the primary steel production in the EU is expected to be decarbonised by 2030 using renewable hydrogen.[64] Other EU-level policies include the Effort Sharing Regulation (ESR), which targets a 40% reduction in emissions below 2005 levels by 2030 for select sectors,[65] the third Renewable Energy Directive (REDIII), which aims to increase the share of renewable energy in the EU's total energy consumption to 42.5%, with a potential increase to 45%,[66] and the EU Emissions Trading Scheme (ETS) which includes the introduction of the Carbon Border Adjustment Mechanism (CBAM) which aims to put a price on carbon emitted during the production of carbon intensive goods that are entering the EU, including that of iron and steel.[67] Germany also has its own ambitious policies, such as the Climate Action Programme 2030 and the Climate Change Act (Klimaschutzgesetz),[68] reflecting the region's strong commitment to decarbonising its economy.

The EU steel industry has achieved a 50% reduction in emissions since 1960 and targets further reduction to 80-95% by 2050 compared to 1990 levels. This ambitious goal relies on hydrogen-based steel production as the primary methodology alongside Direct Reduced Iron (DRI), Carbon Capture Utilisation and Storage (CCUS) and Electric Arc Furnace (EAF) technologies.[13] A list of some of these efforts, outside of Germany, have been provided in **Table 6**.

Table 6: European Green Iron and Steel Efforts

Location	Project Name	Details
Sweden	HYBRIT	○ A joint venture between SSAB, LKAB, and Vattenfall to produce fossil-free steel using hydrogen as the reducing agent.[69]
Sweden	H2 Green Steel Boden	○ A project to build a large-scale green steel production facility using hydrogen, led by H2 Green Steel.[70]
Netherlands	Tata Steel IJmuiden Plant	○ Expressed ambition to produce hydrogen-based green steel by 2030.[71]
Austria	Voestalpine H2FUTURE	○ Green hydrogen pilot facility commences operation with future plans to use green hydrogen for steel decarbonisation.[72]
UK	Liberty Steel GREENSTEEL Strategy	○ Commitment to low-carbon steel production using steel scrap recycling, electric arc furnaces and renewable energy.[73]

Within Germany, there are currently plans for nine steel producing sites to transition to carbon-neutral processes in the future.[74] Details of each site and current status are provided in **Table 7**. Companies involved in this transition include ArcelorMittal, Salzgitter, Huttenwerke, Thyssenkrupp, and SHS Stahl Holding Saar GmbH & Co KgaA.

Table 7: Steel plant transition in Germany[74]

Location	Plant Name	Announcement
Eisenhüttenstadt, Brandenburg	ArcelorMittal Eisenhüttenstadt Steel Plant	○ Transition from BF-BOF to DRI-EAF by 2030. With DRI-EAF plant to be installed by 2026 ○ DRI process will initially operate on natural gas, with plans to operate on hydrogen ○ Development of electrolysis plant and H_2 filling station in 2024
Bremen	ArcelorMittal Bremen Steel Plant	○ Phase out plant's BF-BOF capacity by 2030. With DRI-EAF plant to be installed by 2026 ○ Convert one BF to inject natural gas instead of coal (reducing CO_2 emissions) ○ Install a 12 MW electrolyser in 2024 ○ HyBit H_2-DRI project to be online 2024
Hamburg	ArcelorMittal Hamburg Steel Plant	○ Build a DRI demonstration plant initially operating on natural gas with plans to switch to H_2-DRI by 2026 ○ Convert existing DRI plants to utilise green hydrogen, aiming to achieve 1 mtpa of fossil-free steel production by 2030
Duisburg, North Rhine-Westphalia	ArcelorMittal Duisburg Steel Plant	○ Transition from BOF to EAF steelmaking by 2030
Duisburg, North Rhine-Westphalia	ThyssenKrupp Duisburg Steel Plant	○ Build a DRI plant with integrated melting unit to produce green steel (tkH2Steel) ○ Plant is expected to be completed by 2025 and have a capacity of 1.2 mtpa
Duisburg, North Rhine-Westphalia	Hüttenwerke Krupp Mannesmann (HKM) steel plant	○ Replace BF-BOF process with H_2-DRI-EAF ○ Shutdown one BF in 2025 and second by 2045
Salzgitter, Lower Saxony	Salzgitter Flachstahl Steel Plant	○ Cut emissions from plant by 95% by 2033 ○ Replace BF-BOF with H_2-DRI-EAF by 2033 ○ Begin operation of new plant by 2026
Völklingen, Saarland	Saarstahl Völklingen Steelmaking Plant	○ Transition away from BF-BOF production by building an EAF, to be commissioned by 2027
Dillengen, Saarland	AG der Dillinger Hüttenwerke Dillingen Steel Plant	○ Transition away from BF-BOF production by adding DRI-EAF capacity by 2027, with plans to shut down the BF by 2030 ○ Commission an additional EAF by 2045

Role for Global Collaboration

Renewable energy sources require a relatively high amount of land compared to fossil or nuclear systems for equivalent energy output.[75] Given Germany's high population density and lower levels of solar radiation, Germany encounters challenges in securing sufficient land for the deployment of renewable energy.[76] Moreover, Germany's own hydrogen strategy recognises that producing the substantial quantities of renewable energy required for the energy transition solely within Germany is improbable due to limitations in the country's renewable energy generation capacity.[77] Consequently, Germany has developed a hydrogen import strategy, aiming to import hydrogen and its derivatives, such as ammonia and methanol, to meet an estimated 50-70% of domestic demand.[78]

Despite being highly industrialised, Germany has limited natural resources and depends heavily on imported energy and raw materials – a trait that is common to many industrialised economies such as South Korea and Japan.[79] This is evident through Germany's iron and steel industry being reliant on both raw mineral and energy imports to sustain production. However, these imports must become carbon neutral for the country to achieve its ambitious net-zero targets. This requires the development of international partnership to sustain the necessary renewable energy and raw material imports needed to sustain a green steel industry in Germany.

3 Australia's Role in Global Iron and Steel Markets

Australia is a global leader in providing high quality iron ore. Given the growing demand for zero-carbon products, Australia has huge potential in providing green iron ore, iron and potentially even steel products to the international market.

3.1 A Global Supplier of Iron Ore

Australia is the largest iron ore exporter in the world, exporting 886 million tonnes of iron ore in 2022, projected to reach 917 million tonnes in 2024.[5] With abundant high-quality iron ore resources, an estimated 70 billion tonnes at 62% Fe with a high ore to product ratios (1.2:1), Australia holds a competitive edge in the international iron ore market.[80] The primary iron ore types in Australia are hematite, mainly found in Pilbara, Western Australia, and magnetite, mined in South Australia. Approximately 96% of Australia's iron ore exports are hematite.[81] A summary of some major Australian iron ore mines in Western Australia and South Australia is provided in **Figure 10**.

Australia exports more than double the second-largest supplier of iron ore, Brazil, meeting 57% of global demand.[5] Due to current iron and steel production methods, the downstream emissions from Australia's iron ore exports are estimated to be approximately three times that of Australia's national greenhouse gas emissions.[82] The export of iron ore generated approximately A$124 billion in revenue in 2022[83] and directly employs an estimated 38,000 people.[84] The primary importers of Australian ore include China (745 million tonnes), Japan (57 million tonnes), and South Korea (48 million tonnes), with the EU importing 632.9 thousand tonnes in 2022. Three companies hold 82% of Australian iron ore exports, Rio Tinto (29%), BHP (27%) and Fortescue Metals Group (26%).[85]

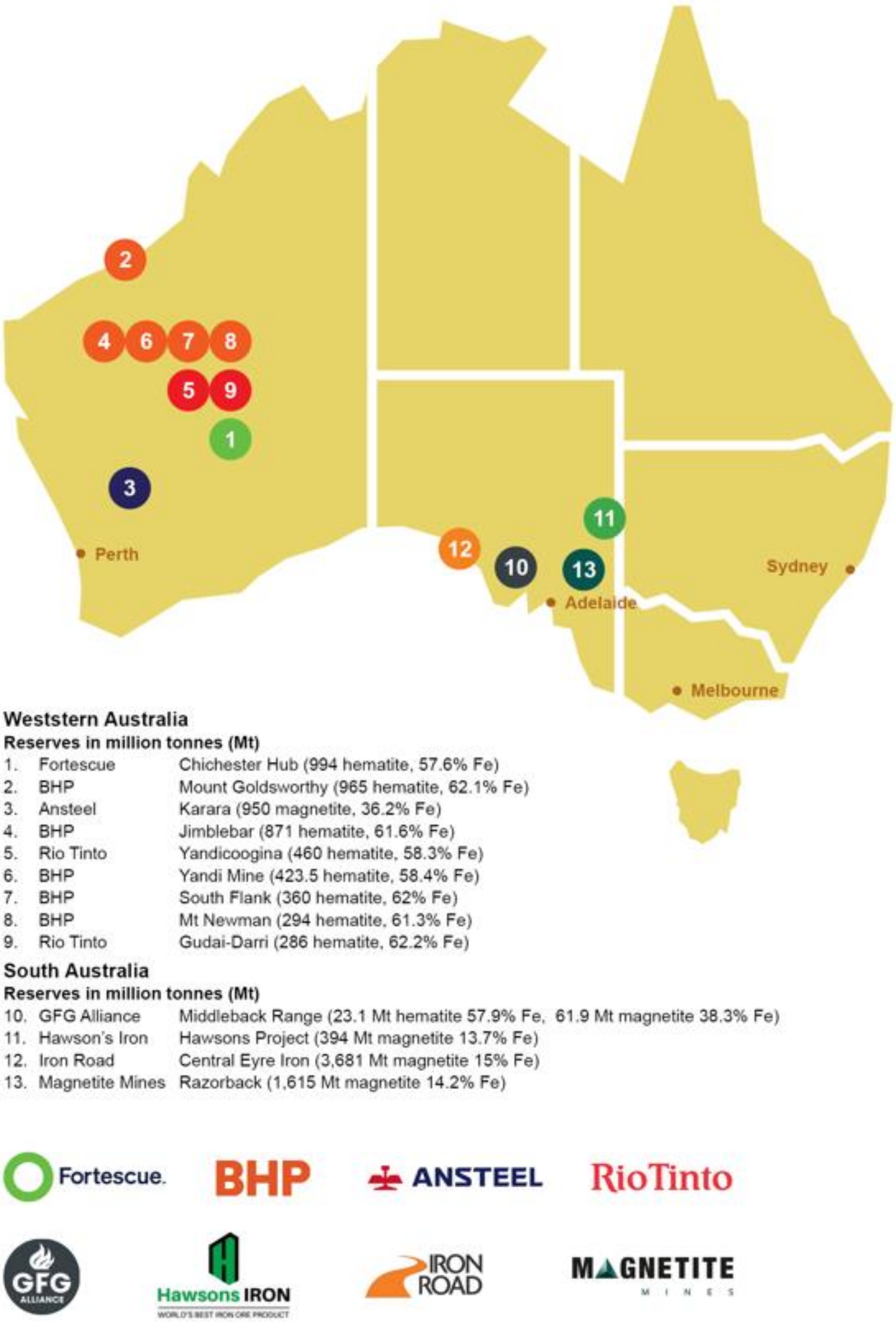


Figure 10. Major Iron Ore Mining Sites in Western Australia and South Australia.[86,87] Current estimates place total Australian Iron Ore reserves at 23,034 million tonnes,[88] these reserves are sufficient to meet German demand for iron ore (34.4 million tonnes in 2022)[40] for over 600 years

3.2 Australian Iron and Steel Production

By global standards, steel production in Australia is relatively small, producing only 5.8 million tonnes of steel in 2021.[3] Australia has three major steel making companies (Bluescope, GFG Alliance and InfraBuild),[85] employing an estimated 52,100 personnel in primary steel manufacturing.[89] A summary of the major steel products produced in Australia are provided in **Table 8**.

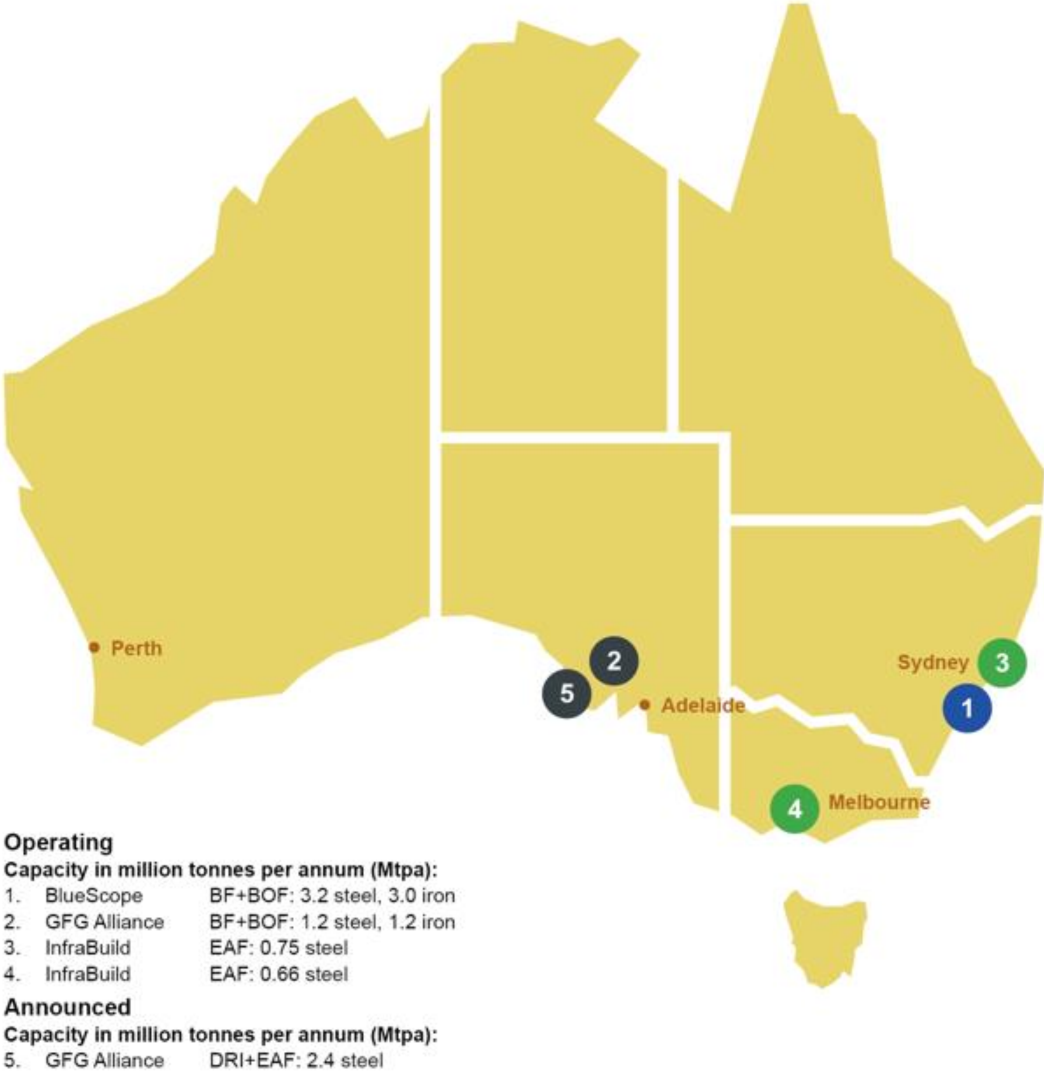
Table 8. Australian Steel Production in 2021[90]

Product	2021 Production (million tonnes)
Pig Iron	3.751
Crude Steel	5.780
Hot Rolled Long Products	1.733
Hot Rolled Flat Products	3.115
Railway Tracks	0.090[1]
Hot Rolled Bars	1.079
Wire Rod	0.654
Hot Rolled Coil, Sheet, and Strip (<3mm)	2.763
Other Metal Coated Sheet and Strip (excl. Tin Mill Products)	1.749
Non-metallic Coated Sheet and Strip	0.887

1. Value for 2020.

Australia currently exports five major steel products with a total value of A$1.047 billion.[90] This encompasses 0.711 million tonnes of semi and finished steel products, 0.118 million tonnes of ingots and semis, 0.155 million tonnes of long products, 0.375 million tonnes of flat products, and 0.063 million tonnes of tubular products.[90] In 2022, key export destinations for Australia's iron and steel in primary forms include New Zealand (1.12 thousand tonnes), Singapore (3 tonnes), and the USA (0.4 tonnes).[91]

The following **Figure 11** shows the total operating and announced iron and steel plants in Australia.



BlueScope InfraBuild GFG ALLIANCE

Figure 11. Current Operating and Announced Iron and Steel Plant Capacity in Australia. BlueScope steel represents Australia's largest steel manufacturers.

3.3 Australia’s Green Hydrogen Transition and Ambition for Green Iron and Green Steel

Australia is a nation with vast renewable energy generation potential, estimated to be approximately 400 times higher than the country’s current energy demand.[92] This, coupled with Australia’s track record for providing large-scale export focused energy projects make it an ideal candidate to be a future net exporter of renewable energy through energy carriers such as green hydrogen and its derivatives.[93] Australia currently has one of the largest pipeline of renewable hydrogen projects in the world,[94] reinforcing the notion that Australia will play a pivotal role in the future exports of green hydrogen and related products.[92,95-100]

The Australian government's commitment to renewable energy development is evident in the National Hydrogen Strategy, aiming for global hydrogen leadership by 2030 focusing on both export and decarbonising domestic industries.[101] This commitment is further emphasised by recent funding announcements including A$4 billion for the Hydrogen Headstart program, A$300 million for the Advancing Hydrogen Fund, over A$500 million for the Australian Regional Hydrogen Hubs Program, up to A$3 billion from the National Reconstruction Fund for renewables and low emissions technologies and the announcement of a A$1.7 billion Future Made in Australia Innovation Fund focussing on priority industries including green metals.[102-106] Additionally, proposed tax incentives, such as the Hydrogen Production Tax Incentive, will provide a A$2 incentive per kilogram of renewable hydrogen produced for up to ten years per project, as well as, the Critical Minerals Production Tax Incentive which offers a tax offset of 10% for the costs of processing critical minerals currently listed in Australia.[107] The Australian government is also making significant progress in facilitating the sourcing of low-emission products by businesses and trading partners through the development of better markets and product standards for green products. The Guarantee of Origin scheme will measure and certify emissions intensity across the supply chain of key products, with focus on renewable hydrogen, and support of the expansion of the program to green metals and low-carbon fuels.[108]

Although there is considerable interest in the development of green hydrogen (and its derivatives, such as ammonia and methanol) for use as a global energy vector,[109] the demand and need for these products at scale is yet to be realised globally and would require significant modification of existing infrastructure for wide-scale adoption. In contrast, green iron for steelmaking could provide a lower barrier to entry, as Australia’s abundant renewable energy resources could be embedded into these commodities and exported to international markets as green iron and potentially green steel products, enabling direct use and application. This potential is highlighted in the recent accompanying reports: the *South Australian Green Iron Supply Chain Study*[110] and the *South Australia-NW Europe via Rotterdam Green Steel Supply Chain Analysis.*[111] These reports investigate the feasibility of producing green iron in South Australia by leveraging the region's abundant renewable energy and magnetite iron ore resources and exporting to north-western Europe. Their findings suggest that incorporating green iron produced in South Australia for green steel production in Germany could result in a 21% reduction in production costs compared to producing green steel in Germany from raw materials.[111]

Australia's low carbon iron and steel plans includes the following project announcements and developments outlined in **Table 9**.

Table 9: Australian Green Iron and Steel Efforts

Project Name	Details
Port Hedland Green Steel Project-	○ Port Hedland Green Steel Project-Stage 1 to produce hot briquetted iron (HBI) at a production capacity of 2 million tonnes per annum.[112]
Collie Green Steel Mill	○ Collie Green Steel Mill in the advanced stages of reaching final investment decision (FID), with an investment of A$400 million.[113]
Mid West DRI Plant	○ Mid West DRI Plant, with an investment of A$1.5 billion, expected to reach FID in 2025.[113]
Low-Temperature Direct Electrochemical Reduction Process	○ Development of a low temperature direct electrochemical reduction process for green iron production by Australian iron ore mining company Fortescue.[114,115]
Christmas Creek Green Iron Pilot Plant	○ Announcement of the Christmas Creek Green Iron pilot plant, by Australian iron ore mining company Fortescue, with an investment of A$50 million and first green iron production expected for 2025.[116]
BioIron Process Pilot Plant	○ Development of a pilot plant to develop the low-carbon iron using biomass, known as the BioIron process by Australian iron ore mining company Rio Tinto.[117]
Gladstone Green Iron Project	○ Commencement of the development phase of proposed Green Iron Project in Gladstone, Queensland by global investment manager, Quinbrook Infrastructure Partners.[118]
Electric Smelting Furnace Pilot Plant	○ Agreement between Australian iron ore mining company BHP and engineering company Hatch to co-design an electric smelting furnace pilot plant to enable the production of green iron from Pilbara ore.[119]
Port Kembla Renewable Hydrogen Projects	○ A memorandum of understanding (MoU) between international energy company Shell and Australian steel company BlueScope Steel to develop renewable hydrogen projects to decarbonise their operations at their Port Kembla facility.[120]

Australia has the potential to develop a new green export sector valued at an estimated A$333 billion annually, to meet the demand for low-carbon products like green iron or green steel, renewable hydrogen, ammonia, green aluminium, and critical minerals, which are poised to drive global economic growth in this century.[121] However, swift action is crucial to secure early market positioning, as delayed efforts risk competitive advantage against other green iron and steel producers, and therefore potential declines in both iron ore and fossil fuel exports, leaving insufficient time to replace Australia's lost export income.[121]

4 An Opportunity for Partnerships

The synergy of Australia's abundant renewable energy, iron ore resources and strong international relationships has the potential to establish a value-added green metals supply chain between Australia and Germany.

The German iron and steel industry currently is, and expects to remain, an important part of the German economy.[28] However, this industry must decarbonise if Germany is to achieve its ambitious net-zero targets. As this industry is highly dependent on energy and raw material imports,[33,40,122] with Germany currently importing 34.4 million tonnes of iron ore and 0.19 million tonnes of pig iron in 2022,[33,40] any decarbonisation of this sector must also consider the decarbonisation of these value chains.

Furthermore, as Germany faces challenges surrounding renewable energy deployment, such as securing sufficient land for the development of renewable energy[76], it will likely need to rely on the import of renewable energy to meet its future renewable energy ambitions.[93,123,124] The combination of these factors means that Germany has a strong interest in developing a global green iron for steel market, which will not only create new value-added trade relationships, but facilitate Germany in decarbonising its steel industry.

4.1 Why Australia and Germany?

Australia and Germany are natural partners in a low-carbon iron and steel value chain. Australia's vast renewable energy resources, large-scale export credentials and ability to deliver large-scale energy and resource projects make it well-placed for the development of a low-carbon green iron and green steel value chains. Germany's strong net-zero commitments[125] and expertise in iron and steel manufacturing[126] make an ideal fit to import green iron or even green steel and co-develop Australia's infrastructure and manufacturing capabilities to deliver these products. Furthermore, both governments have already shown early initiative in the development of a green hydrogen export value chain[93] and explored the mutual benefits the formation of early partnerships have in the development of these industries.

Australia and Germany are closely linked with over 1 million Australian residents of German descent. Germany ranks as **Australia's eleventh largest trading partner** with a trade volume amassing to over A$28.9 billion in 2022-23. Australian investment stock in Germany in 2022 totalled A$71.6 billion, while Germany's total investment stock in Australia was valued at A$52.5 billion. German investment spans automotive and manufacturing, information and communications technology, agriculture, pharmaceuticals, defence, energy, and health.[127]

Over 380 German companies, spanning advanced manufacturing, logistics, transport, banking, materials, and clean energy, employ over 58,000 people in Australia. Conversely, over 160

Australian companies, focusing on infrastructure, finance, and energy, have a presence in Germany, providing jobs for about 17,000 personnel.[127] Furthermore, there are over 600 institutional agreements between Australian and German research institutions with cooperations between 181 German universities and 49 Australian universities.[128] Notably, this collaboration extends to the hydrogen sector, indicating significant cooperation between Australia and Germany in the renewable energy space.[93]

This is reinforced by the bilateral agreements already in place between Australia and Germany. The two nations are working together across multiple streams of cross-government and industry collaboration including science, climate change adaptation, clean energy and critical minerals sectors. In 2021, Australia and Germany signed The Australia-Germany Hydrogen Accord,[129] the first of its kind by the German government.[127] The accord emphasises strategic and close partnership and determination to work together through such projects as the jointly funded feasibility study to investigate the Australian-German supply chain of hydrogen produced from renewables *The Australia-Germany Hydrogen from Renewable Energy Supply Chain Feasibility Study (HySupply)*,[93] and the *German-Australian Hydrogen Innovation and Technology Incubator (HyGate)*.[130] This includes collaboration through the Australian Hydrogen Council (AHC), German-Australian Chamber of Industry & Commerce (AHK) as well as through the German-Australian Hydrogen Alliance.[93]

In 2022, the European **green steel market was valued at an estimated US$47.36 million**, and is expected to **reach US$1.27 billion by 2028**.[131] This is primarily driven by two factors, emissions reductions objectives and end-user demand.[132] This upward trend is expected to lead to an expansion in the production and supply of renewable energy resources and green iron and steel in the European steel market.

The synergy of abundant renewable energy, iron ore resources and strong international relationships has the potential to establish a value-added supply chain between Australia and Germany, fostering the production and export of green iron for green steel. This would enhance Australia's iron, steel, and renewable energy industries, whilst enabling Germany to decarbonise its steel industry and meet their net-zero ambitions.

Australia and Germany are already forming partnerships with the following announcements surrounding the supply of renewable energy, iron, and steel:

- Rio Tinto and Salzgitter recently signed a Memorandum of Understanding (MoU) to explore the use of Rio Tinto iron ore in green steelmaking.[133]
- Fortescue Future Industries (FFI) and E.ON, recently signed a Memorandum of Understanding (MoU) to deliver up to five million tonnes per annum of renewable hydrogen to Europe by 2030.[134]
- Australia and Germany signed a joint Declaration of Intent to work together to develop critical minerals value chains.[135]

Through the development of renewable energy and adoption of green iron ore mining, ironmaking and steelmaking techniques, Australia can decarbonise the entire green steel value chain. Thus, enabling exploration of three potential opportunities that Australia could provide in the advancement of green steel production in Germany:

i) Export iron ore and renewable hydrogen (and derivatives) to enable the integrated production of green iron and green steel in Germany,
ii) Produce green iron locally in Australia and export green iron and renewable hydrogen (and derivatives) to support the production of green steel in Germany,
iii) Produce both green iron and green steel locally in Australia for export to Germany. The steel would still generally require further processing into the specialty steels used in German and European steel markets.

At present, we acknowledge that the first two options are likely the better fits for current industry arrangements in both Australia and Europe.

4.2 Potential Australia to Germany Export Corridor

Australia currently exports most of its iron ore from Port Hedland (in Western Australia)[136] and Port Augusta (in South Australia).[137] Europe imports a majority of its iron and steel products through the Port of Rotterdam (in the Netherlands).[37] Germany imports a majority of its bulk goods through Hansaport in Hamburg and liquefied natural gas through Wilhelmshaven and Brunsbüttel ports.

An export corridor could be established linking Australian ports to German ports on the North or Baltic seas, potentially focusing on Hansaport in Hamburg, Wilhelmshaven and Brunsbüttel ports. The corridor could also extend to include the Port of Rotterdam in the Netherlands (**Figure 12)**. This could provide green energy (in the form of renewable hydrogen and derivatives), iron ore, iron for steelmaking or green steel to the German market. Moreover, this export corridor is not confined to Australia and Germany; the entire European market can benefit from the imports of any proposed export commodity.

Figure 12. Proposed Export Corridor Between Australia and Europe. An export corridor could be developed between Australia and Europe to provide green iron ore, iron, steel, or renewable energy.

5 Conclusion and Next Steps

The global iron and steel industry is a major contributor to greenhouse gas emissions, accounting for 7-9% of global carbon emissions and nearly a quarter of global industrial emissions. However, it also plays a crucial role in global decarbonisation efforts due to its importance in sustainable infrastructure and clean energy technologies. Iron and steel production in the European Union contributes an estimated 4% of the EU's total carbon dioxide emissions, with Germany leading as the largest steel producer in Europe. Australia currently stands as the largest global exporter of iron ore and metallurgical coal for iron and steel making, and the downstream emissions associated with these iron ore exports are around three times Australia's total national greenhouse gas emissions. Germany's ambitions to decarbonise its economy, coupled with Australia's ambitions to become a global net exporter of renewable energy, presents an extraordinary opportunity to reduce global emissions while adding value to both Australian and German industries.

This report highlighted the potential opportunities and synergies between Australia and Germany in establishing a green metal supply chain that can be used for ironmaking and steelmaking in Germany. Such collaboration not only facilitates the decarbonisation of the German iron and steel industries but also opens new export opportunities for Australia. This report forms the first part of a series of three reports. The second report will delve into the different technology pathways available for green iron and steel production and the third report will perform a techno economic assessment of a potential green iron and steel value chain between Australia and Germany.

6 References

1 International Energy Agency (IEA). *Iron and Steel Technology Roadmap. Towards more sustainable steelmaking*, <https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf> (2020).

2 Spoerl, J. S. A brief history of iron and steel production. (2004).

3 Worldsteel Association. *World Steel in Figures 2023*, <https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2023-4.pdf> (2023).

4 Worldsteel Association. *World Steel in Figures*, <https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2024.pdf> (2024).

5 Australian Government Department of Industry Science and Resources Office of the Chief Economist. *Resources and Energy quarterly: September 2023*, <https://www.industry.gov.au/publications/resources-and-energy-quarterly-september-2023> (2023).

6 The Observatory of Economic Complexity (OEC). *Iron Ore*, <https://oec.world/en/profile/hs/iron-ore> (2024).

7 Dutta, S. K. & Sah, R. Direct reduced iron: Production. *Encyclopedia of Iron, Steel, and Their Alloys*, 1082-1108 (2016).

8 Nduagu, E. I. *et al.* Comparative life cycle assessment of natural gas and coal-based directly reduced iron (DRI) production: A case study for India. *Journal of Cleaner Production* **347**, 131196 (2022).

9 Worldsteel Association. *Sustainability performance of the steel industry 2004-2022*, <https://worldsteel.org/wp-content/uploads/Sustainability-indicators-report-2023.pdf> (2023).

10 Worldsteel Association. *World Steel in Figures*, <https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/> (2023).

11 International Energy Agency (IEA). *Industry*, <https://www.iea.org/energy-system/industry> (2023).

12 International Energy Agency (IEA). *Coal 2023 analysis and forecast to 2026*, <https://iea.blob.core.windows.net/assets/a72a7ffa-c5f2-4ed8-a2bf-eb035931d95c/Coal_2023.pdf> (2023).

13 Ali Hasanbeigi, A. S. What is Green Steel? Definitions and Scopes from Standards, Initiatives, and Policies around the World. 1-86 (Jan 2023).

14 International Energy Agency (IEA). CO2 emission in 2022. (2023).

15 Kim, J., Sovacool, B.K., Bazilian, M., Griffiths, S., Lee, J., Yang, M. and Lee, J. Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. *Energy Research & Social Science* **89**, 102565, doi:https://doi.org/10.1016/j.erss.2022.102565 (2022).

16 Berger, R. The future of steelmaking–How the European steel industry can achieve carbon neutrality. *Roland Berger GMBH* (2020).

17 World Trade Organsiation (WTO). *Trade forum for decarbonization standards: Promoting coherence and tranparency in the steel sector*, <https://www.wto.org/library/events/event_resources/tbt_09032023/informal_summary.pdf> (2023).

18 World Trade Organsiation (WTO). *Decarbonization standards and the iron and steel sector: how can the WTO support greater coherence?*, <https://www.wto.org/english/tratop_e/envir_e/trade-climate-change_info_brief_no7_e.pdf> (2022).
19 Green Hydrogen Organsiation (GH2). *Green Hydrogen Standard. The Global Standard for Green Hydrogen and Green Hydrogen Derivatives including Green Ammonia*, <https://gh2.org/sites/default/files/2023-01/GH2_Standard_A5_JAN%202023_1.pdf> (2023).
20 Australian Government Department of Climate Change Energy the Environment and Water (DCCEEW). *Australian National Greenhouse Accounts Factors For individuals and organisations estimating greenhouse gas emissions* <https://www.dcceew.gov.au/sites/default/files/documents/national-greenhouse-account-factors-2023.pdf> (2023).
21 International Energy Agency (IEA). *Achieving Net Zero Heavy Industry Sectors in G7 Members*, <https://iea.blob.core.windows.net/assets/c4d96342-f626-4aea-8dac-df1d1e567135/AchievingNetZeroHeavyIndustrySectorsinG7Members.pdf> (2022).
22 Responsible Steel. *ResponsibleSteel International Standard Version 2.0*, <https://www.responsiblesteel.org/wp-content/uploads/2022/10/ResponsibleSteel-Standard-2.0.1.pdf> (2022).
23 Wirtschaftsvereinigung Stahl. *Green Steel Definition - A Labelling System for Green Lead Markets*, <https://www.stahl-online.de/wp-content/uploads/2022-11-25_Green-Steel-Definition-A-Labelling-System-for-Green-Lead-Markets.pdf> (2022).
24 Encyclopedia Britannica. *Bessemer process*, <https://www.britannica.com/topic/2023-The-Year-in-Review> (2023).
25 Chem Europe. *Open hearth furnace*, <https://www.chemeurope.com/en/encyclopedia/Open_hearth_furnace.html> (2023).
26 History Skills. *Coal and Iron in the Industrial Revolution*, <https://www.historyskills.com/classroom/year-9/yr-9-coal-and-iron-reading/> (2023).
27 European Commission. *Towards competitive and clean European steel*, <https://commission.europa.eu/system/files/2021-05/swd-competitive-clean-european-steel_en.pdf> (2021).
28 EUROFER. European Steel in Figures 2023. (2023).
29 Wisevoter. *Steel Production by Country 2023*, <https://wisevoter.com/country-rankings/steel-production-by-country/#germany > (2023).
30 Worldsteel Association. *Annual production steel data*, <https://worldsteel.org/steel-topics/statistics/annual-production-steel-data/?ind=P1_crude_steel_total_pub/CHN/IND/DEU> (2023).
31 United Nations Comtrade (UN). *Pig Iron Import to EU*, <https://comtradeplus.un.org/TradeFlow?Frequency=A&Flows=M&CommodityCodes=720110&Partners=0&Reporters=97&period=2022&AggregateBy=none&BreakdownMode=plus> (2023).
32 United Nations Comtrade (UN). *EU exports of Pig Iron*,

<https://comtradeplus.un.org/TradeFlow?Frequency=A&Flows=M&CommodityCodes=720110&Partners=0&Reporters=97&period=2022&AggregateBy=none&BreakdownMode=plus> (2023).

33 United Nations Comtrade (UN). *Germany import and export of Pig Iron*, <https://comtradeplus.un.org/TradeFlow?Frequency=A&Flows=X&CommodityCodes=720110&Partners=0&Reporters=276&period=2022&AggregateBy=none&BreakdownMode=plus> (2023).

34 Carolina Liljenstolpe, R. H., Hans Selbach, Daniel Larsson and Stig Abrahamsson Statistics of the Swedish Mining Industry 2022. (2023).

35 Geological Survey of Sweden (SGU). *Mining Staistics*, <https://www.sgu.se/en/mineral-resources/mineral-statistics/> (2023).

36 Mining Data Online. *Kiruna Mine*, <https://miningdataonline.com/property/493/Kiruna-Mine.aspx> (2023).

37 Port of Rotterdam. *Iron Ore*, <https://www.portofrotterdam.com/en/logistics/cargo/dry-bulk/iron-ore> (2023).

38 Europa (EUstats). *Dry bulk gross weight of dry bulk goods handled in each port*, <https://ec.europa.eu/eurostat/databrowser/view/mar_qg_qm_pwhb__custom_7851102/default/bar?lang=en> (2023).

39 GMK Center. *Global iron ore market trend: EU and Ukraine's prospects*, <https://gmk.center/en/posts/global-iron-ore-market-trendiron-eu-and-ukraines-prospects/> (2023).

40 United Nations Comtrade (UN). *Germany imports of Iron ore and concentrates*, <https://comtradeplus.un.org/TradeFlow?Frequency=A&Flows=X&CommodityCodes=2601&Partners=0&Reporters=276&period=2022&AggregateBy=none&BreakdownMode=plus> (2023).

41 German Ports. *German Ports Guide*, <https://www.rostock-port.de/fileadmin/user_upload/Broschuere_German_Ports_englisch_web_low.pdf> (2014).

42 Port of Hamburg. *Port of Hamburg*, <https://www.hafen-hamburg.de/en/terminals/#> (2023).

43 GMK Center. *EU could become scrap importer in less than 5 years – forecast*, <https://gmk.center/en/news/eu-could-become-scrap-importer-in-less-than-5-years-forecast/> (2023).

44 Andrew Gadd, N. T., Xinliang Liu, Rod Dukino. *BHP Pathways to decarbonisation episode seven: the electric smelting furnace*, <https://www.bhp.com/news/prospects/2023/06/pathways-to-decarbonisation-episode-seven-the-electric-smelting-furnace> (2023).

45 GMK Center. *Germany cut its scrap exports to a 13-year low in 2022*, <https://gmk.center/en/news/germany-cut-its-scrap-exports-to-a-13-year-low-in-2022/#:~:text=In%202022%2C%20the%20import%20of,3.1%25%20y%2Fy).> (2023).

46 Dworak, S. F. J. Steel scrap generation in the EU-28 since 1946 – Sources and composition. Resources, Conservation and Recycling. **173**, p.105692, doi:https://doi.org/10.1016/j.resconrec.2021.105692 (2021).

47 Daigo, I. & Goto, Y. Comparison of tramp element contents of steel bars from Japan

and China. *ISIJ International* **55**, 2027-2032 (2015).
48 Port of Rotterdam. *Scrap Metal*, <https://www.portofrotterdam.com/en/logistics/cargo/dry-bulk/scrap-metal> (2023).
49 Elango, S. *Life cycle assessment of coal based direct-reduced iron production in India*, (2020).
50 Dutta, S. K. a. C., Y.B. *Basic Concepts of iron and steel making*. (Springer Nature, 2020).
51 International Energy Agency (IEA). *Coal, Analysis and forecast to 2025*, <https://iea.blob.core.windows.net/assets/91982b4e-26dc-41d5-88b1-4c47ea436882/Coal2022.pdf> (2022).
52 Clean Energy Wire. *Germany EU remain heavily dependent on imported fossil fuels*, <https://www.cleanenergywire.org/factsheets/germanys-dependence-imported-fossil-fuels> (2023).
53 Reuters. *German coal imports rose 8% in 2022 Russia sold 37% less*, <https://www.reuters.com/markets/commodities/german-coal-imports-rose-8-2022-russia-sold-37-less-data-2023-02-27/#:> (2023).
54 European Council. *Where does the EU's gas come from?*, <https://www.consilium.europa.eu/en/infographics/eu-gas-supply/> (2023).
55 European Commission. *REPowerEU: Joint European action for more affordable, secure and sustainable energy*, <https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_1512> (2022).
56 Bundesnetzagentur (Federal Network Agency). *Bundesnetzagentur publishes gas supply figures for 2022*, <https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/EN/2023/20230105_RueckblickGas2022.html#:> (2023).
57 Pierre Jean Cunat. Alloying Elements in Stainless Steel and Other Chromium-Containing Alloys. (2004).
58 World Integrated Trade Solution (WITS). *Germany ferro-alloys and ferro-nickel imports by country in 2022*, <https://wits.worldbank.org/trade/comtrade/en/country/DEU/year/2022/tradeflow/Imports/partner/ALL/product/720260> (2023).
59 Encyclopedia Britannica. *Flux*, <https://www.britannica.com/technology/flux-metallurgy> (2016).
60 European Commission. *Competitiveness of the European Cement and Lime Sectors*, <https://publications.europa.eu/resource/cellar/06d2851d-07cd-11e8-b8f5-01aa75ed71a1.0001.01/DOC_1#:> (2018).
61 TrendEconomy. *European Union Imports and Exports of Limestone flux*, <https://trendeconomy.com/data/h2/EuropeanUnion/2521> (2023).
62 TrendEconomy. *German Imports and Exports of Limestone Flux*, <https://trendeconomy.com/data/h2/Germany/2521> (2023).
63 IndexBox. *Imports of Limestone Flux and Limestone in Germany*, <https://www.indexbox.io/search/price-for-limestone-flux-and-limestone-germany/> (2023).
64 European Commission Joint Research Centre. *EU climate targets: how to decarbonise*

the steel industry, <https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/eu-climate-targets-how-decarbonise-steel-industry-2022-06-15_en#_ftn2> (2022).

65 Climate Action Tracker. *Policies and Action: European Union*, <https://climateactiontracker.org/countries/eu/policies-action/> (2024).

66 Council of the European Union. *Renewable energy: Council adopts new rules*, <https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/renewable-energy-council-adopts-new-rules/#:~:text=The%20current%20renewable%20energy%20directive,by%202030%20at%20EU%20level.> (2023).

67 European Commission. *Carbon Border Adjustment Mechanism*, <https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en#:~:text=The%20EU's%20Carbon%20Border%20Adjustment,production%20in%20non%2DEU%20countries.> (2024).

68 Bundesregierung (The Federal Government of Germany). *Climate Action Programme 2030*, <https://www.bundesregierung.de/breg-en/issues/climate-action#> (2023).

69 HYBRIT. *Fossil-free steel – a joint opportunity!*, <https://www.hybritdevelopment.se/en/> (2024).

70 H2 Green Steel. *A pioneering venture – starting in Boden*, <https://www.h2greensteel.com/boden> (2024).

71 Tata Steel. *Tata Steel IJmuiden*, <https://www.tatasteelnederland.com/en/About-us/tata-steel-ijmuiden#> (2024).

72 Voestalpine. *H2FUTURE: World's largest "green" hydrogen pilot facility successfully commences operation*, <https://www.voestalpine.com/group/en/media/press-releases/2019-11-11-h2future-worlds-largest-green-hydrogen-pilot-facility-successfully-commences-operation/> (2019).

73 Liberty Steel Group. *Greensteel*, <https://libertysteelgroup.com/uk/greensteel/> (2024).

74 Global Energy Monitor. *Tracker Map*, <https://globalenergymonitor.org/projects/global-steel-plant-tracker/tracker-map/> (2023).

75 Hannah Ritchie. *How does the land use of different electricity sources compare?*, <https://ourworldindata.org/land-use-per-energy-source> (2022).

76 Ponitka, J. & Boettner, S. Challenges of future energy landscapes in Germany—a nature conservation perspective. *Energy, Sustainability and Society* **10**, 1-11 (2020).

77 Federal Ministry for Econmic Affairs and Climate Action. *The National Hydrogen Strategy*, <https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html> (2020).

78 Federal Ministry for Econmic Affairs and Climate Action. *Federal Cabinet adopts import strategy for hydrogen and hydrogen derivatives*, <https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2024/07/20240724-import-strategy-hydrogen.html> (2024).

79 Encyclopedia Britannica. *Germany: Resources and power*, <https://www.britannica.com/place/Germany/Resources-and-power> (2023).

80 Minerals Conuncil of Australia. *Australian Iron ore: When Quality meets opportunity*, <https://minerals.org.au/wp-content/uploads/2023/01/Best-in-Class-Australian-Iron-Ore-2021.pdf> (2021).
81 Geoscience Australia. *Iron Ore*, <https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/iron-ore> (2024).
82 CSIRO. *Steeling ourselves: How Australia can support the transition to net-zero steel*, <https://www.csiro.au/en/news/All/Articles/2022/May/Net-zero-steel> (2022).
83 Department of Foreign Affairs and Trade (DFAT). *Annual Report 2022-23*, <https://www.dfat.gov.au/sites/default/files/dfat-annual-report-2022-23.pdf> (2023).
84 IBIS World. *Iron Ore Mining in Australia - Market Size, Industry Analysis, Trends and Forecasts (2024-2029)*, <https://www.ibisworld.com/au/industry/iron-ore-mining/65/#Methodology> (2024).
85 Global Data. *Iron ore production in Australia and major projects*, <https://www.mining-technology.com/data-insights/iron-ore-in-australia-2/?cf-view> (2023).
86 Mining Data Online. *Mining Data Solutions*, <https://miningdataonline.com/> (2023).
87 Department for Energy and Mining (DEM). *South Australia's Major Operating/Approved Mines Resource Estimates and Production Statistics*, <https://www.energymining.sa.gov.au/industry/minerals-and-mining/mining/major-projects-and-mining-activities> (2023).
88 Geoscience Australia. *Australia's Estimated Ore Reserves*, <https://www.ga.gov.au/digital-publication/aimr2022/australias-estimated-ore-reserves> (2023).
89 Steel Fabrication Services. *Steel in Australia*, <https://steelfabservices.com.au/steel-in-australia/> (2023).
90 Australian Steel Institute. *Capabilities of the Australian steel industry to supply major projects in Australia*, <https://www.steel.org.au/getattachment/10e081fd-17cf-40a8-be33-442bd8dbe6e4/Steel-Industry-Capability-document-110222.pdf> (2023).
91 United Nations Comtrade (UN). *Iron and steel in ingots or other primary forms*, <https://comtradeplus.un.org/TradeFlow?Frequency=A&Flows=X&CommodityCodes=7206&Partners=0&Reporters=36&period=2022&AggregateBy=none&BreakdownMode=plus> (2022).
92 Carbon Tracker Initiative. *The Sky's the Limit: Solar and wind energy potential.*, <https://carbontracker.org/reports/the-skys-the-limit-solar-wind/> (2021).
93 R. Daiyan, I. M., R. Amal, S. Kara, K.F. Aguey-Zinsou, M.H. Khan, K. Polepalle, W. Rayward-Smith. The Case for an Australian Hydrogen Export Market to Germany: State of Play Version 1.0. UNSW Sydney, Australia. (2021).
94 Department of Climate Change Energy the Environment and Water (DCCEEW). *$2 billion program to power Australian renewable hydrogen industry opens*, <https://minister.dcceew.gov.au/bowen/media-releases/2-billion-program-power-australian-renewable-hydrogen-industry-opens> (2023).
95 Pflugmann, F. & De Blasio, N. *Geopolitical and market implications of renewable hydrogen: new dependencies in a low-carbon energy world*. (Belfer Center for Science and International Affairs, 2020).

96 Hydrogen Council & McKinsey & Company. *Hydrogen Insights: A perspective on hydrogen investment, market development, and cost competitiveness*, <https://hydrogencouncil.com/en/hydrogen-insights-2021/> (2021).
97 Matich B. *Green hydrogen to reach cost parity by 2030*, <https://www.pv-magazine-australia.com/2019/11/15/green-hydrogen-to-reach-cost-parity-by-2030/> (2019).
98 Acil Allen Consulting. *Opportunities for Australia from Hydrogen Exports*, <https://arena.gov.au/assets/2018/08/opportunities-for-australia-from-hydrogen-exports.pdf> (2018).
99 International Energy Agency (IEA). *The Future of Hydrogen. Seizing today's opportunities*, <https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf> (2019).
100 International Renewable Energy Agency (IRENA). *A New World. The Geopolitics of the Energy Transformation*, <https://www.irena.org/publications/2019/Jan/A-New-World-The-Geopolitics-of-the-Energy-Transformation> (2019).
101 Department of Climate Change Energy the Environment and Water (DCCEEW). *Australia's National Hydrogen Strategy*, <https://www.dcceew.gov.au/energy/publications/australias-national-hydrogen-strategy> (2023).
102 Australian Government Department of Climate Change Energy the Environment and Water (DCCEEW). *Hydrogen Headstart program*, <https://www.dcceew.gov.au/energy/hydrogen/hydrogen-headstart-program> (2024).
103 Australian Renewable Energy Agency (ARENA). *Hydrogen Headstart Round 1*, <https://arena.gov.au/funding/hydrogen-headstart/> (2023).
104 Australian Renewable Energy Agency (ARENA). *Hydrogen Headstart Round 2*, <https://arena.gov.au/funding/hydrogen-headstart-round2/> (2024).
105 Australian Trade and Investment Commission. *Hydrogen Australia's next big export industry*, <https://international.austrade.gov.au/en/do-business-with-australia/sectors/energy-and-resources/hydrogen#> (2024).
106 Australian Government Department of Industry Science and Resources. *Green metals A Future Made in Australia: Unlocking Australia's Green Iron, Steel, Alumina and Aluminium Opportunity*, <https://storage.googleapis.com/converlens-au-industry/industry/p/prj2e0a68bed1f8b62c9c631/page/green_metals_consultation_paper.pdf> (2024).
107 Australian Government Australian Tax Office (ATO). *Hydrogen Production and Critical Minerals Tax Incentives*, <https://www.ato.gov.au/about-ato/new-legislation/in-detail/businesses/hydrogen-production-and-critical-minerals-tax-incentives> (2024).
108 Australian Government. *Budget 2024-25 A Future Made in Australia*, <https://budget.gov.au/content/factsheets/download/factsheet-fmia.pdf> (2024).
109 Johnston, C., Khan, M. H. A., Amal, R., Daiyan, R. & MacGill, I. Shipping the sunshine: An open-source model for costing renewable hydrogen transport from Australia. *International Journal of Hydrogen Energy* **47**, 20362-20377 (2022).
110 Wang, C. & Walsh, S. South Australian Green Iron Supply Chain Study. (2024).
111 Government of South Australia, P. o. R. *South Australia - NW Europe via Rotterdam.*

Green Steel Supply Chain Analysis, <https://www.energymining.sa.gov.au/__data/assets/pdf_file/0003/1006986/3f3eb52597c8bc4c4cbe0295a0b1647d7a5660e0.pdf> (2024).

112 GMK Center. *Port Hedland Green Steel plans to build a processing plant in Australia*, <https://gmk.center/en/news/port-hedland-green-steel-plans-to-build-a-processing-plant-in-australia/#:~:text=The%20project%2C%20called%20the%20Port,of%20iron%20ore%20per%20year.> (2023).

113 Green Steel WA. *Forging Western Australia's Steel Manufacturing Legacy*, <https://www.greensteelwa.com.au/> (2023).

114 Renew Economy. *Fortescue hails "green iron" breakthrough as own coal-free tech moves to pilot phase*, <https://reneweconomy.com.au/fortescue-hails-green-iron-breakthrough-as-own-coal-free-tech-moves-to-pilot-phase/> (2023).

115 Fortescue. *Low Temperature Direct Electrochemical Reduction for Zero Emissions Iron*, <https://arena.gov.au/assets/2024/06/Fortescue-MIH2-Poster-Lowtemp-DRI.pdf> (2024).

116 Fortescue. *Christmas Creek Green Iron Pilot*, <https://fortescue.com/what-we-do/our-projects/christmas-creek-green-iron-pilot> (2024).

117 RioTinto. *Rio Tinto to develop BioIron™ R&D facility in Western Australia to test low-carbon steelmaking*, <https://www.riotinto.com/en/news/releases/2024/rio-tinto-to-develop-bioiron-rd-facility-in-western-australia-to-test-low-carbon-steelmaking> (2024).

118 Quinbrook Infrastructure Partners. *Quinbrook sponsors development of 'Green Iron' Project in Gladstone Queensland*, <https://www.quinbrook.com/news-insights/quinbrook-sponsors-development-of-green-iron-project-in-gladstone-queensland/> (2024).

119 Renew Economy. *BHP to pilot green smelting furnace using electricity, hydrogen and Pilbara iron ore*, <https://reneweconomy.com.au/bhp-to-pilot-green-smelting-furnace-using-electricity-hydrogen-and-pilbara-iron-ore/> (2023).

120 BlueScope. *BlueScope and Shell join forces in the Illawarra*, <https://www.bluescope.com/news/BlueScope-and-Shell-join-forces-in-the-Illawarra> (2021).

121 Beyond Zero Emissions. *Export Powerhouse: Australia's $333 billion opportunity*, <https://www.bze.org.au/research/report/export-powerhouse#:> (2021).

122 United Nations Comtrade (UN). *Germany import and export of Steel (including stainless and other primary form)*, <https://comtradeplus.un.org/TradeFlow?Frequency=A&Flows=X&CommodityCodes=721810&Partners=0&Reporters=276&period=2022&AggregateBy=none&BreakdownMode=plus> (2023).

123 Eicke, L. & De Blasio, N. The Future of Green Hydrogen Value Chains: Geopolitical and Market Implications in the Industrial Sector. *Environment and Natural Resources Program Reports* (2022).

124 Lebrouhi, B., Djoupo, J., Lamrani, B., Benabdelaziz, K. & Kousksou, T. Global hydrogen development-A technological and geopolitical overview. *International Journal of*

Hydrogen Energy **47**, 7016-7048 (2022).
125 Germany. Update to the long-term strategy for climate action of the Federal Republic of Germany. (Nov 2022).
126 IBIS World. *German Iron and Steel manufacturing*, <https://www.ibisworld.com/germany/industry/iron-steel-manufacturing/768/#IndustryStatisticsAndTrends> (2022).
127 Department of Foreign Affairs and Trade (DFAT). *Germany country brief*, <https://www.dfat.gov.au/geo/germany/germany-country-brief> (2024).
128 Australian Embassy Germany. *Australia-Germany Research Network*, <https://germany.embassy.gov.au/beln/AGRN.html#:> (2023).
129 Ministers for the Department of Industry Science and Resources. *Australia and Germany partner on hydrogen initiatives*, <https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-and-germany-partner-hydrogen-initiatives> (2021).
130 Department of Climate Change Energy the Environment and Water (DCCEEW). *Australia and Germany strengthen hydrogen partnership*, <https://www.dcceew.gov.au/about/news/australia-and-germany-strengthen-hydrogen-partnership> (2023).
131 ResearchandMarkets. *European Green Steel Market: Analysis & Forecast with Impact Analysis of COVID-19 and Forecast up to 2028*, <https://www.researchandmarkets.com/reports/5726040/european-green-steel-market-analysis-and-forecast> (2023).
132 BusinessWire. *European Green Steel Market (by Demand, Supply, Type, End User, & Region): Insights and Forecast with Potential Impact of COVID-19 (2023-2028)*, <https://www.researchandmarkets.com/reports/5897227/> (2023).
133 RioTinto. *Rio Tinto and Salzgitter sign MOU to study using Rio Tinto iron ore in green steelmaking*, <https://www.riotinto.com/en/news/releases/2022/rio-tinto-and-salzgitter-sign-mou-to-study-using-rio-tinto-iron-ore-in-green-steelmaking> (2022).
134 Eon. *Partner on journey to become europe's largest green renewable hydrogen supplier and distributor*, <https://www.eon.com/en/about-us/media/press-release/2022/2022-03-29-fortescue-future-industries-and-eon-partnership.html> (2022).
135 Department of Industry Science and Resources (DISR). *Joint declaration of intent between Australia and Germany on a critical minerals value chain feasibility study*, <https://www.industry.gov.au/publications/joint-declaration-intent-between-australia-and-germany-critical-minerals-value-chain-feasibility-study> (2023).
136 Pilbara Ports Authority. *Port of Port Hedland*, <https://www.pilbaraports.com.au/ports/port-of-port-hedland> (2023).
137 Port Augusta Operations. *Port Augusta*, <https://www.portplayford.com/> (2022).